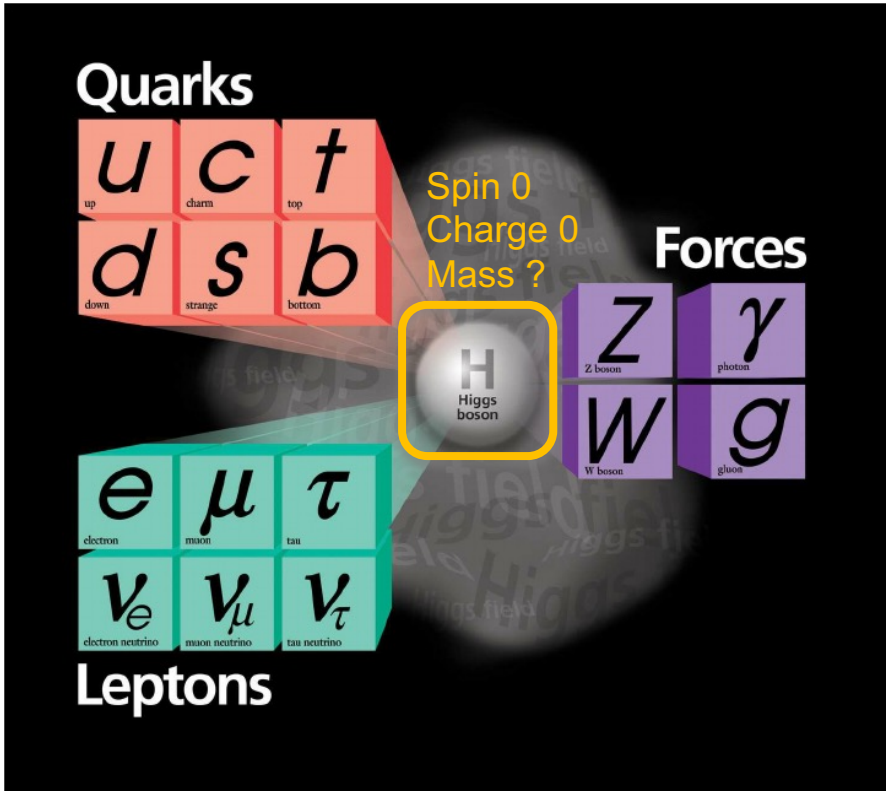
Recent Highlights on Higgs Physics from LHC

Elisabeth Schopf (University of Oxford)
on behalf of the ATLAS & CMS Collaborations

DIS 2021, Stony Brook & virtual world

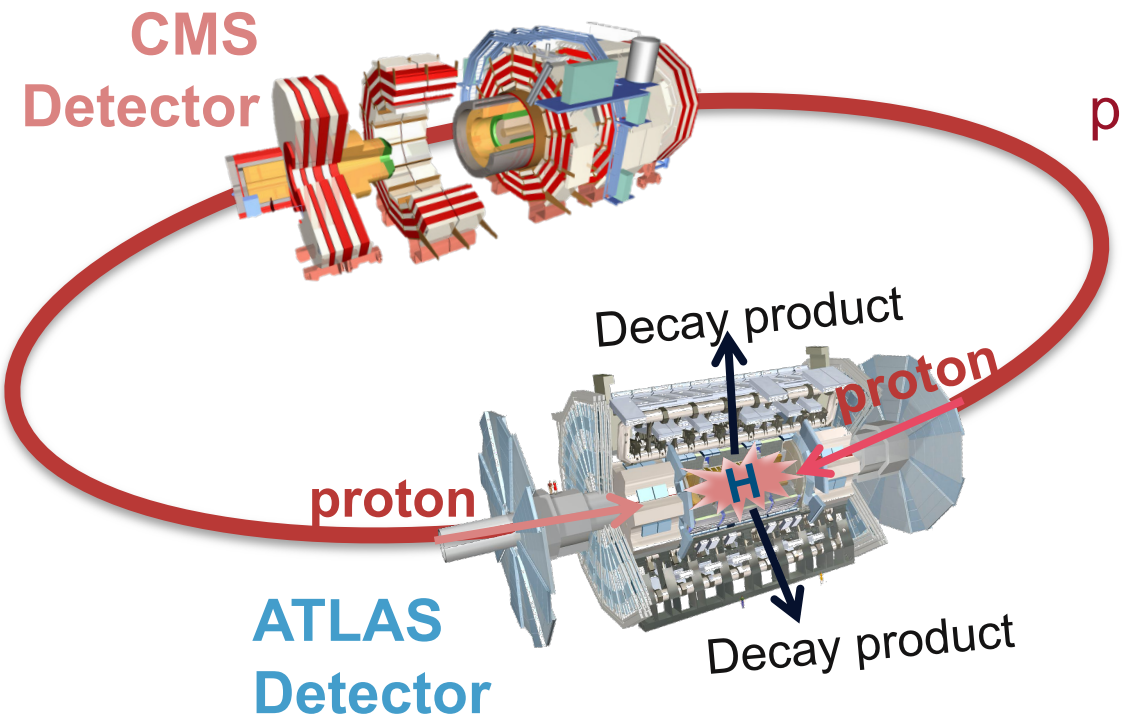
The Standard Model Higgs Boson



- Interaction of particles with Higgs field generate their masses
- Scalar boson associated with field: Higgs boson (H)
- 2012: discovery of the Higgs boson with mass ~125 GeV

→ Knowledge of m_H & assuming SM couplings fixes all predictions for interactions

+ Our Tools to Study Higgs Bosons



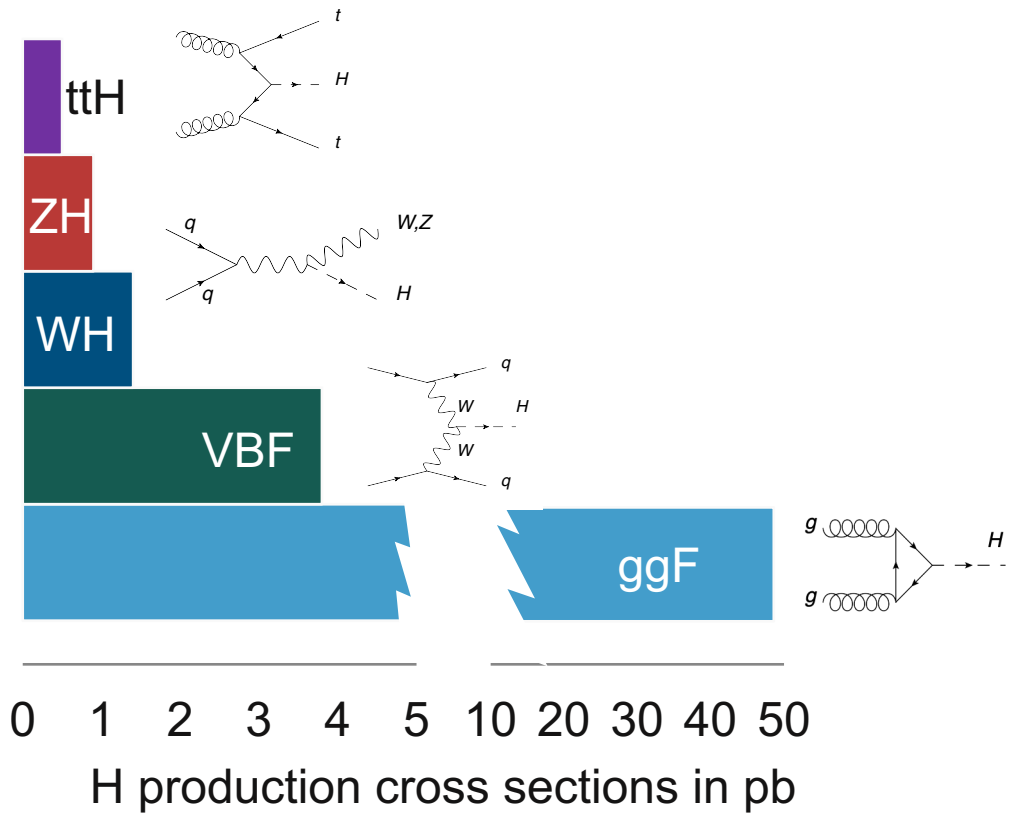
Large Hadron Collider:
pp collisions at $\sqrt{s}$=13 TeV

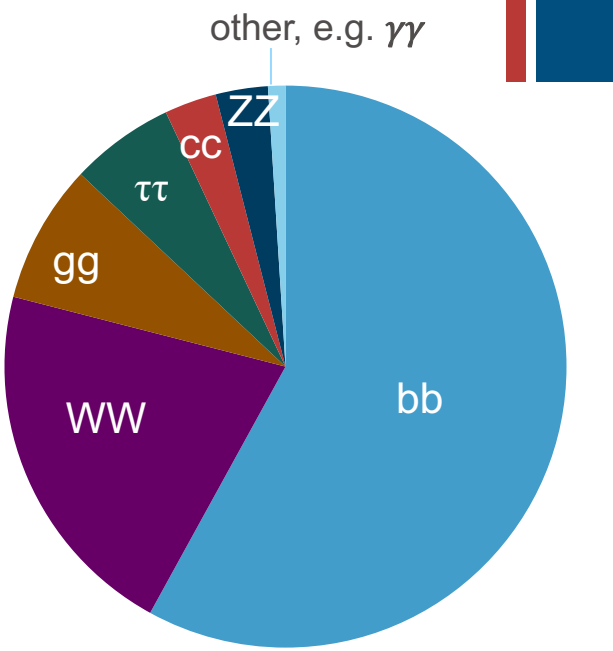
~1 in 10^9 collisions produce Higgs boson

ATLAS and CMS: multi-purpose detectors
LHC Run-2 operation generated large data sets → ~10^7 (SM) Higgs bosons

→ SM Higgs physics transitioned to precision measurement era
→ Large amount of opportunities to search for beyond SM effects

Higgs Production at LHC and Decay Channels





H decay channel branching ratios in %

Probed SM production channels: ggF, VBF, ZH, WH, ttH, tH

Probed SM decays: $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb, $\mu\mu$, $Z/\gamma+\gamma$, cc, meson+Z/γ, ee

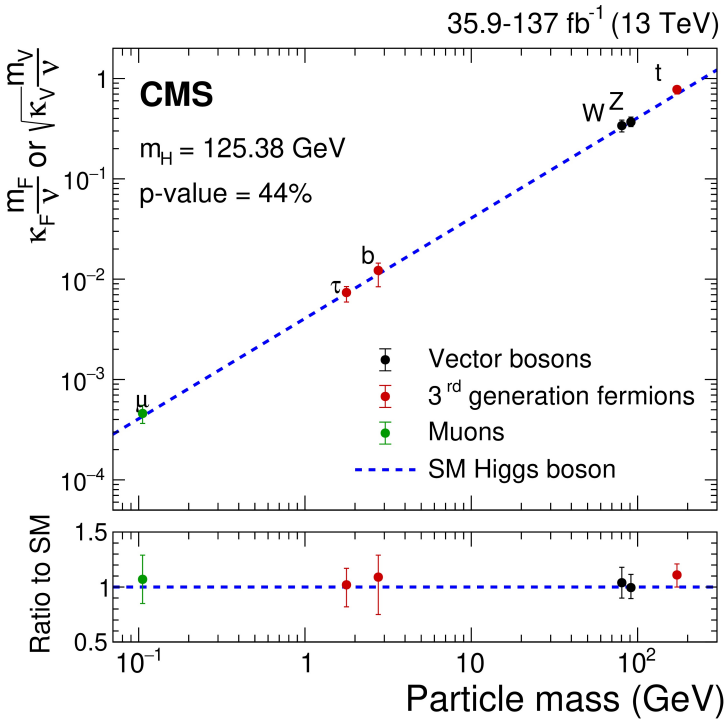
Legend: observed, evidence, searching

Higgs Boson Measurements

Precision measurements
- Mass
- Differential distributions
- …

Higgs boson properties
- Self-coupling
- CP structure
- …

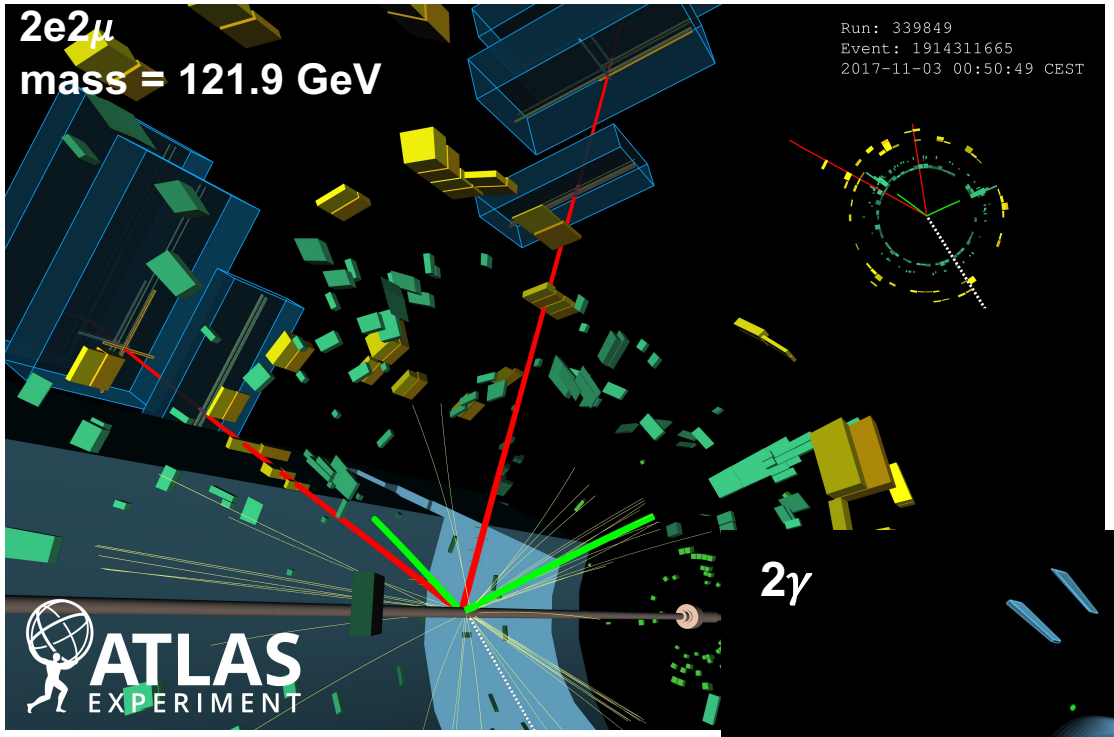
BSM searches and interpretations
- Additional Higgs bosons
- Exotic Decays
- …



Measurements of coupling strengths of H to SM particles

Full list of public ATLAS and CMS Higgs results:
ATLAS Higgs results, CMS Higgs results

H→ZZ* and H→$\gamma\gamma$ Candidate Events



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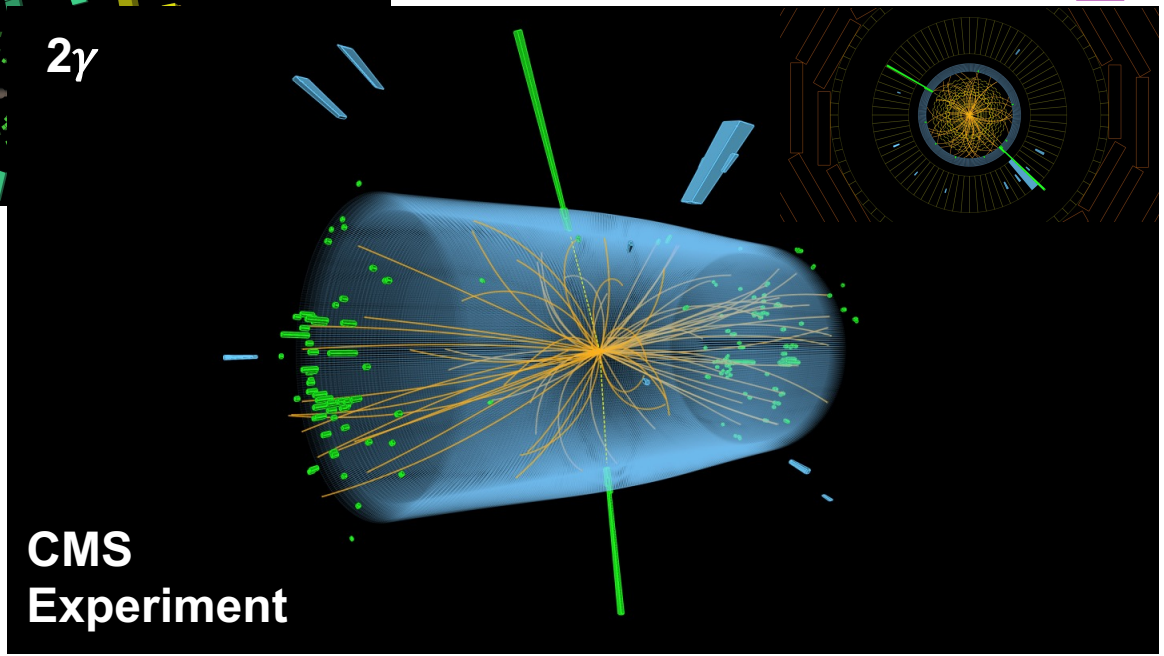


…more details in D. Du's talk on Tue.

Higgs Mass Measurements

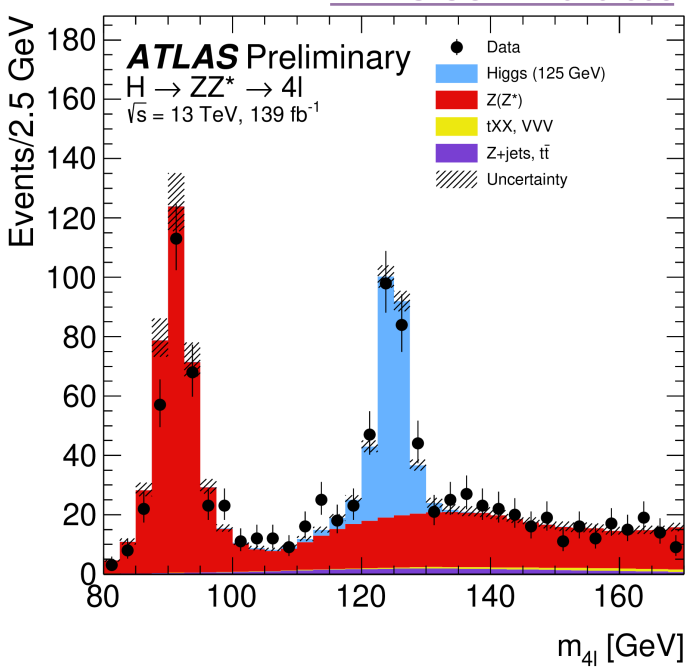
H→ZZ*→4e/4μ/2e2μ and H→$\gamma\gamma$:

fully reconstructed final states with very good energy resolution and well modelled background

ATLAS H→ZZ full Run-2: $m_H = 124.92 \pm 0.19(\text{stat.})^{+0.09}_{-0.06}(\text{syst.})\,\text{GeV}$

CMS H→ZZ+$\gamma\gamma$ Run-1 + 2016 data: $m_H = 125.38 \pm 0.14\,\text{GeV}$

ATLAS-CONF-2020-005



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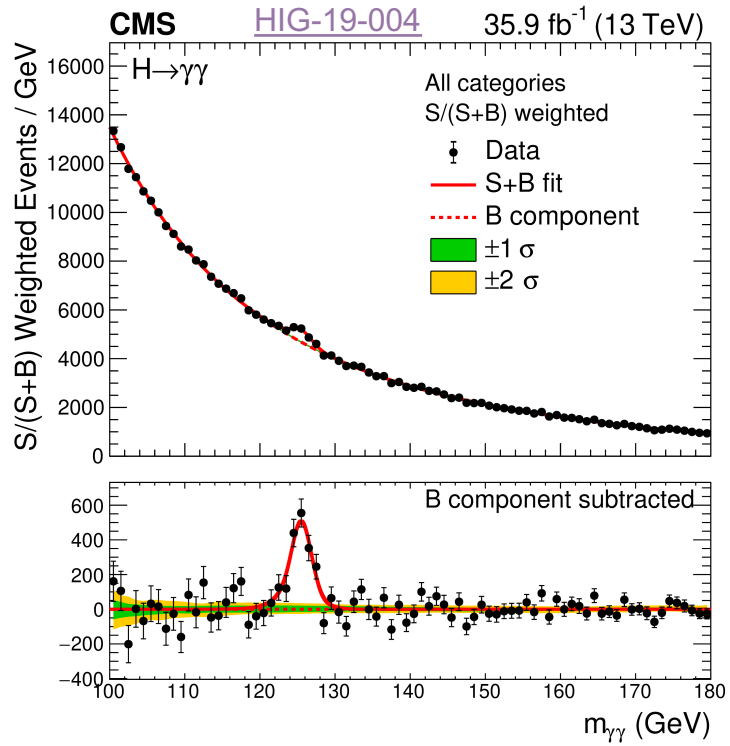
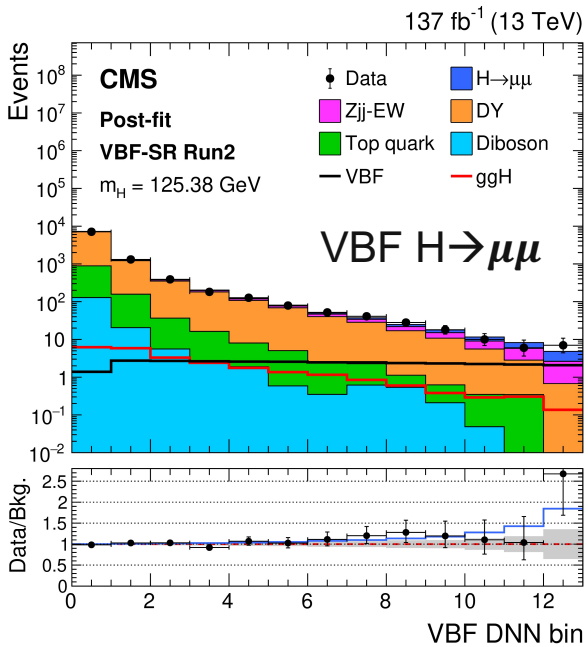
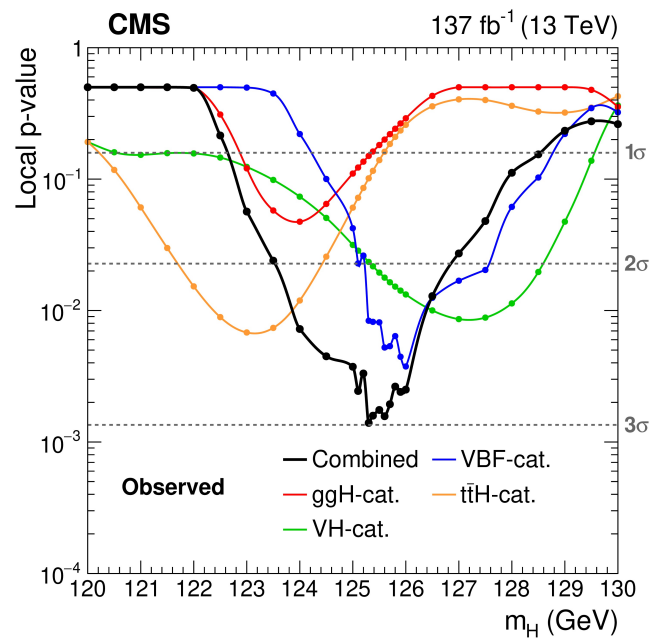


…more details in S.Hirose's talk on Tue.

Evidence for H→$\mu\mu$ Decays

BR(H→$\mu\mu$)=0.02% and large amount of background
Measurement performed in all major H production channels
→ most sensitive for 2nd generation fermion couplings





JHEP 01 (2021) 148

CMS: $\mu = 1.19^{+0.40}_{-0.39}(\text{stat.})^{+0.15}_{-0.14}(\text{syst.})$ Observed significance: 3.0 σ

ATLAS: $\mu = 1.2 \pm 0.6$ Observed significance: 2.0 σ

Phys. Lett. B 812 (2021) 135980

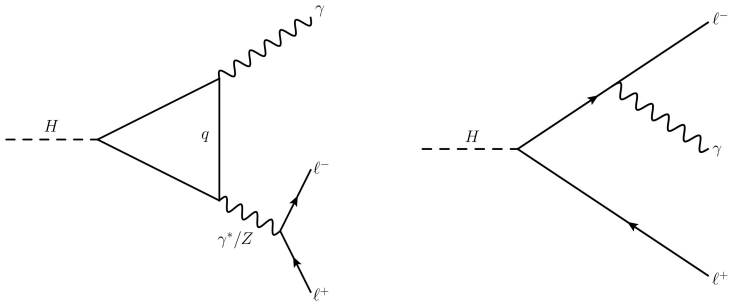
…more details in S.Hirose's talk on Tue.

Evidence for H→$\ell\ell\gamma$ Decays

$\ell\ell$ = ee or $\mu\mu$

March 2021

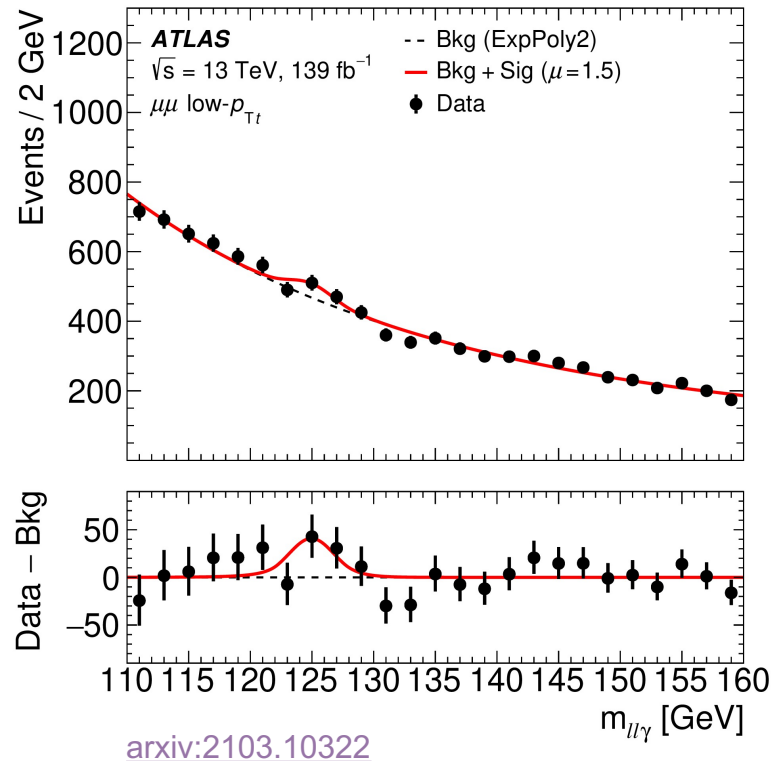
Targets $m_{\ell\ell}$< 30 GeV (BR~10^{-5}): dominated by γ^*→ $\ell\ell$
complements H→Zγ measurements (CMS, ATLAS)



Overlapping showers in EM calorimeter for eeγ signature
→ dedicated event reconstruction and categorisation algorithms

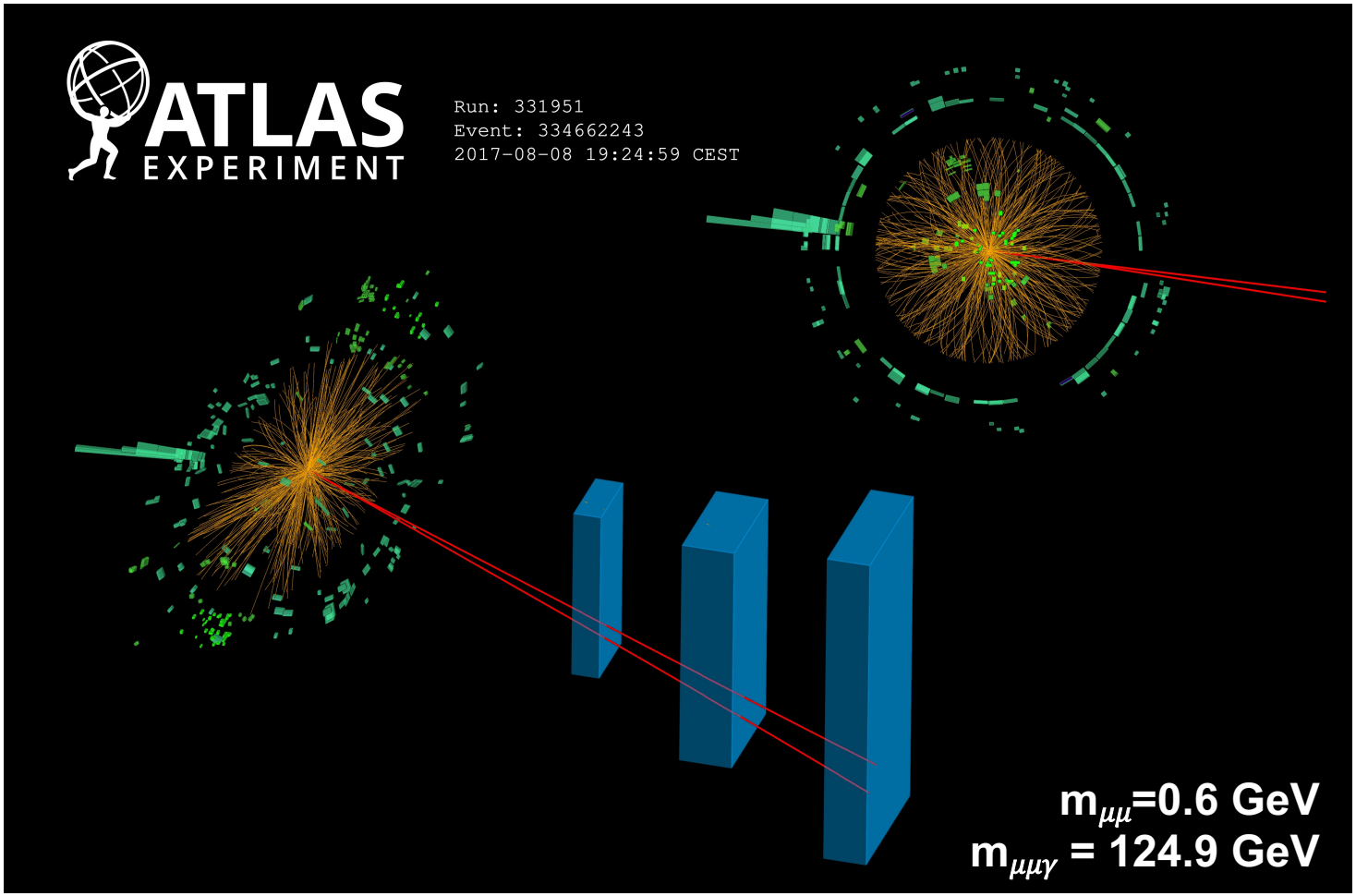
$$\mu = 1.5 \pm 0.5$$

Observed significance: 3.2 σ



arxiv:2103.10322

$H \rightarrow \mu\mu\gamma$ Candidate Event



link

…more details in D. Du's talk on Tue.

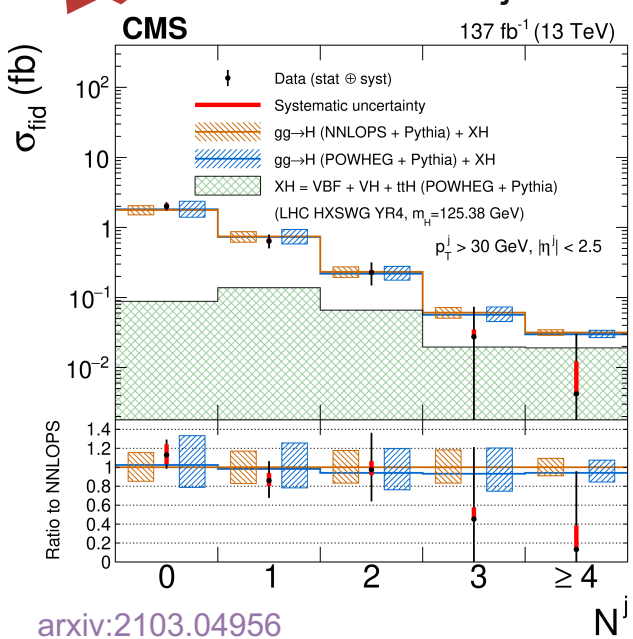
Differential Distributions

H→ZZ*→4e/4μ/2e2μ:

Measurements of H kinematics probes higher order cross section corrections and potential beyond SM contributions

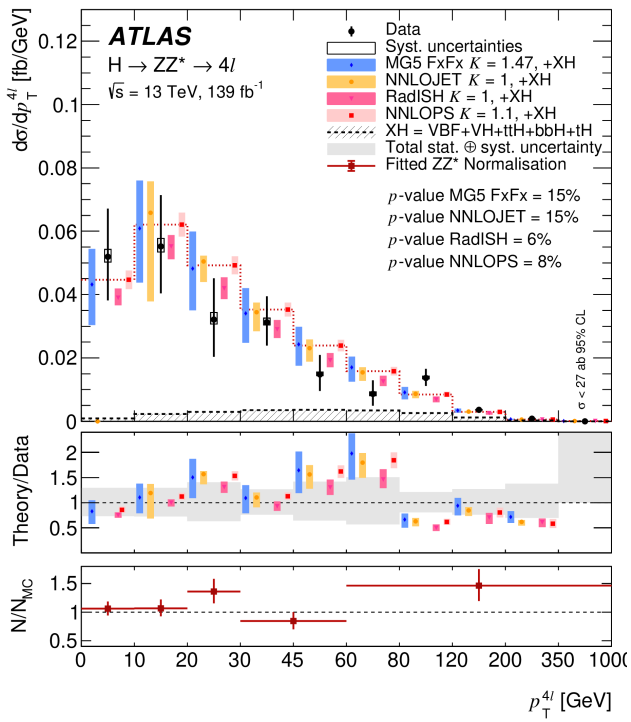
March 2021

Number of jets



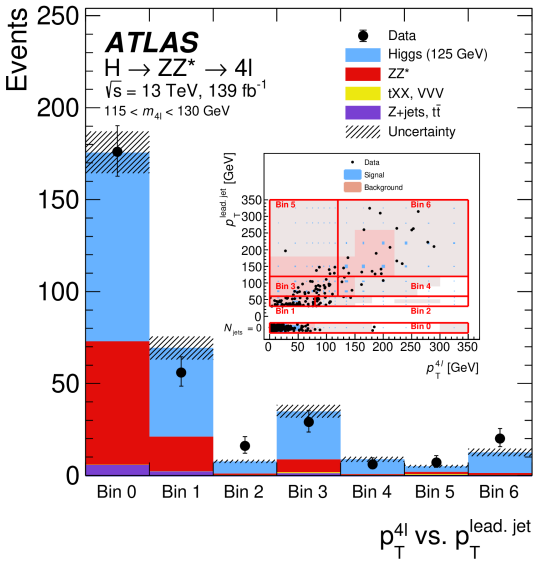
arxiv:2103.04956

H transverse momentum



Eur. Phys. J. C 80 (2020) 942

Start probing 2D differential: e.g. p_T(H) vs. p_T(jet)



differential distributions are also probed in the H→ $\gamma\gamma$ (ATLAS) and H→WW channel (CMS)

…more details in B. Ciungu's talk on Tue.

Simplified Template Cross Sections (STXS)

Quasi-differential cross section measurements

H production phase space split into bins of H kinematics

→ σ*BR templates parametrise expected SM signal yields per bin

→Reinterpretation within anomalous couplings, e.g. EFT, frameworks

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d} \frac{1}{\Lambda^{d-4}} \left(\sum_{i} c_i^{(d)} O_i^{(d)} \right)$$

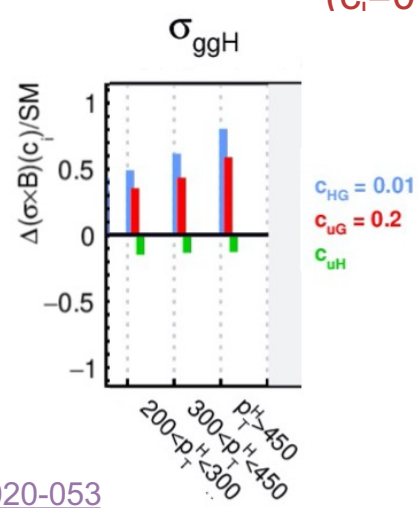
Dimension

Scale of new physics (set to 1 TeV)

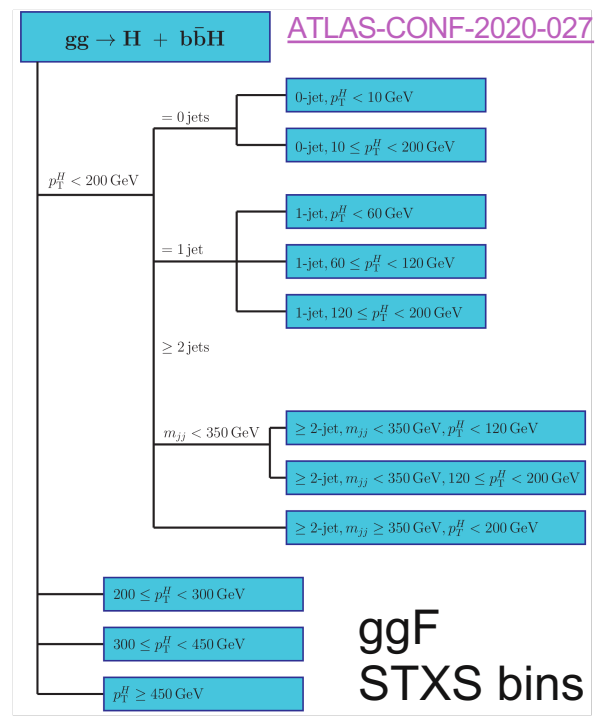
Coupling modifiers (c_i=0 in SM)

Dimension d operators

EFT parametrisation and impact on STXS bin σ*BR



ATLAS-CONF-2020-053



ggF STXS bins

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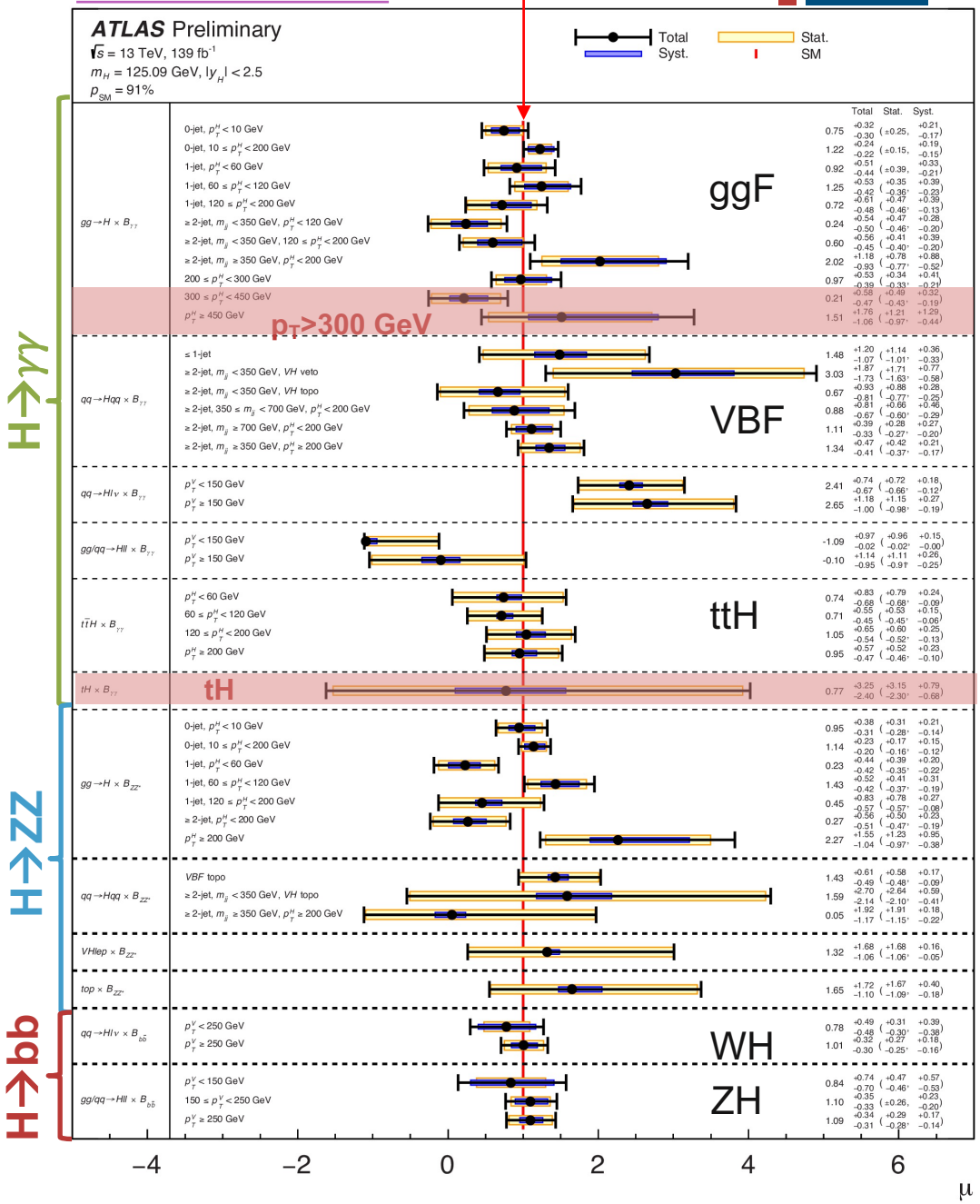
…more details in B. Ciungu's talk on Tue.

+ STXS Combination and EFT Interpretation

ATLAS EXPERIMENT

ATLAS-CONF-2020-053

SM prediction



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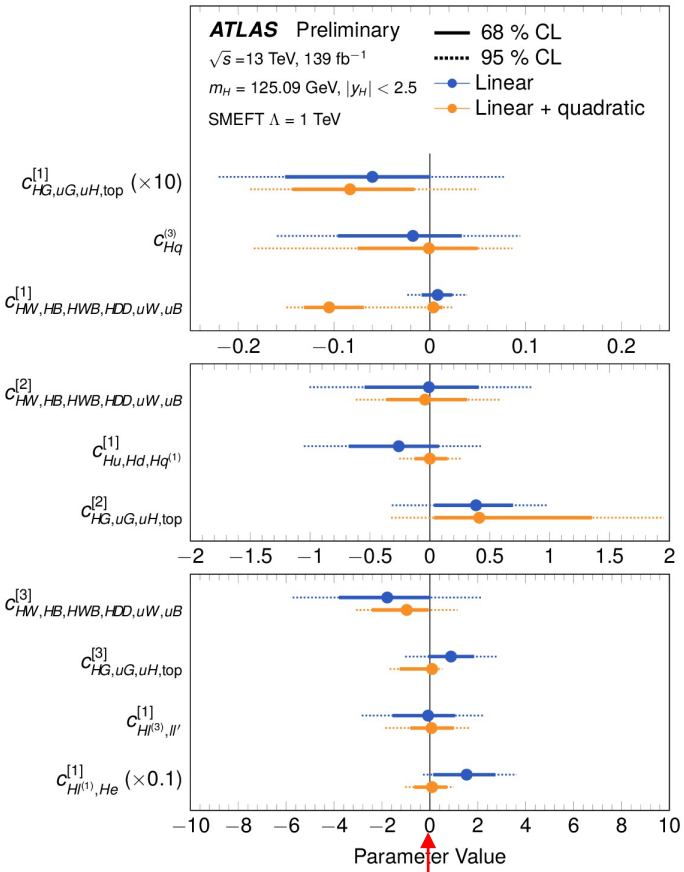

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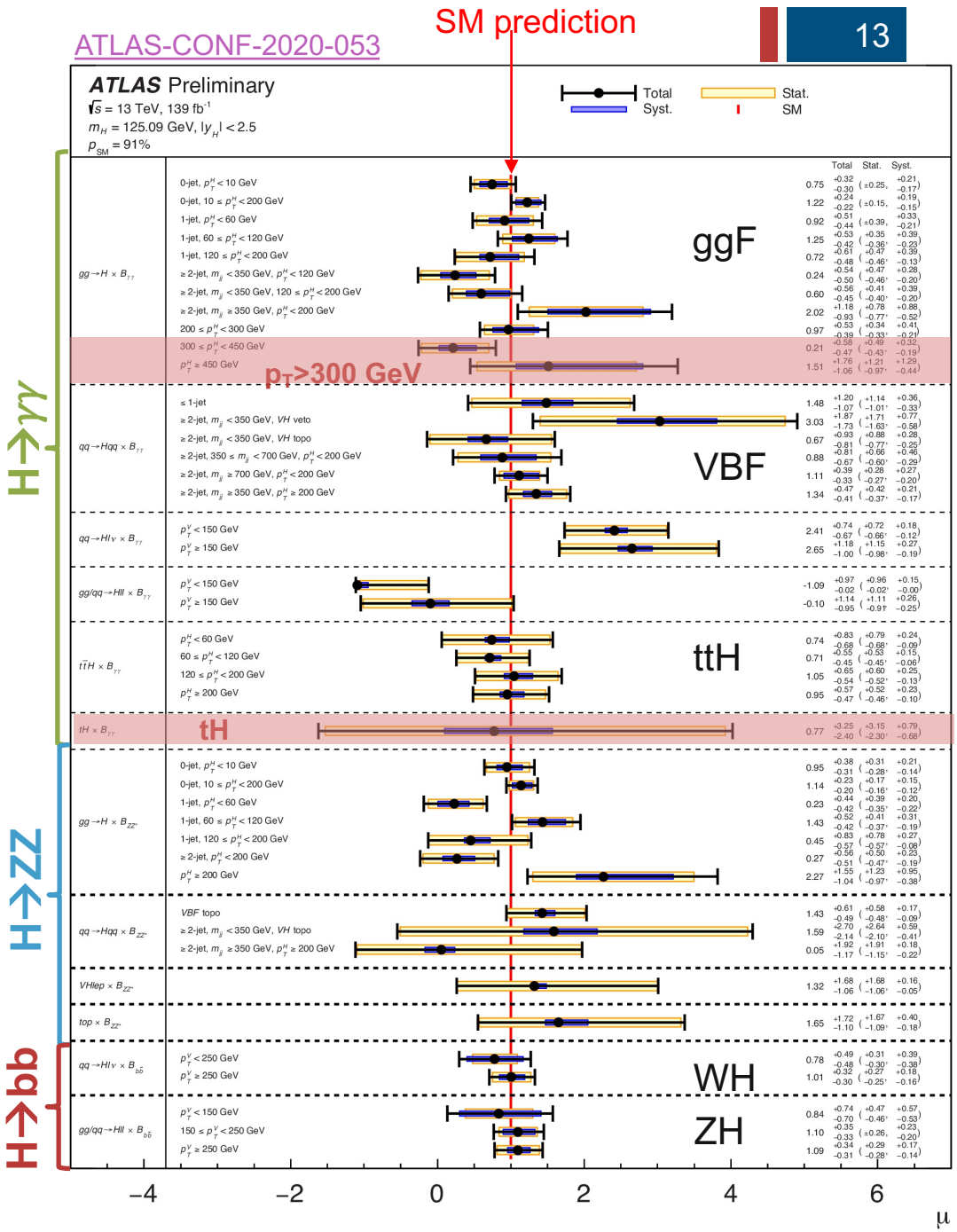
ATLAS-CONF-2020-053

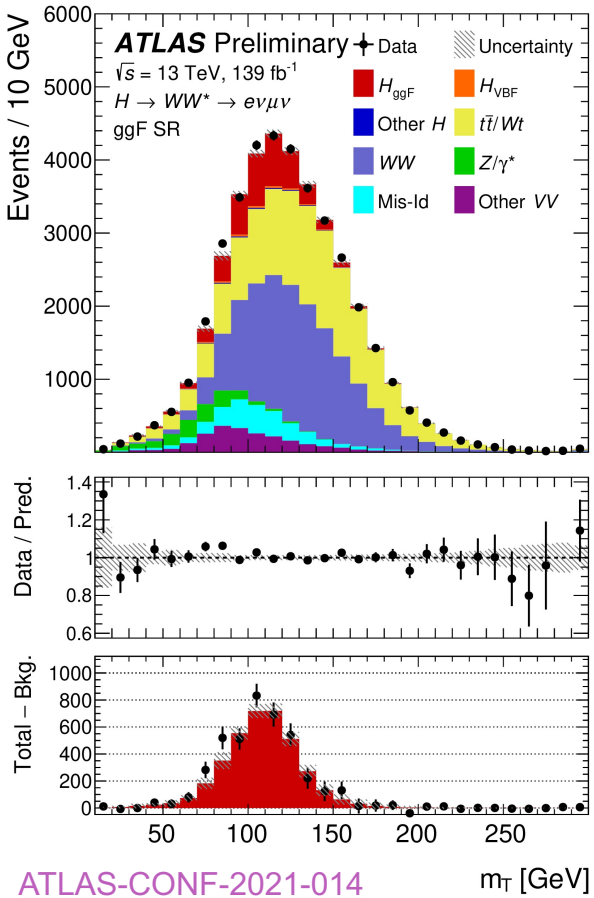


…more details in D. Du's talk on Tue.
…more details in M. Lizzo's talk on Tue.

H→WW Measurements

Large BR (~20%) but final state can't be fully reconstructed due to missing E_T from ν in W decays

→ Improved analysis techniques (e.g. DNNs): increasing precision and start probing VH



ATLAS-CONF-2021-014

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H→WW Measurements

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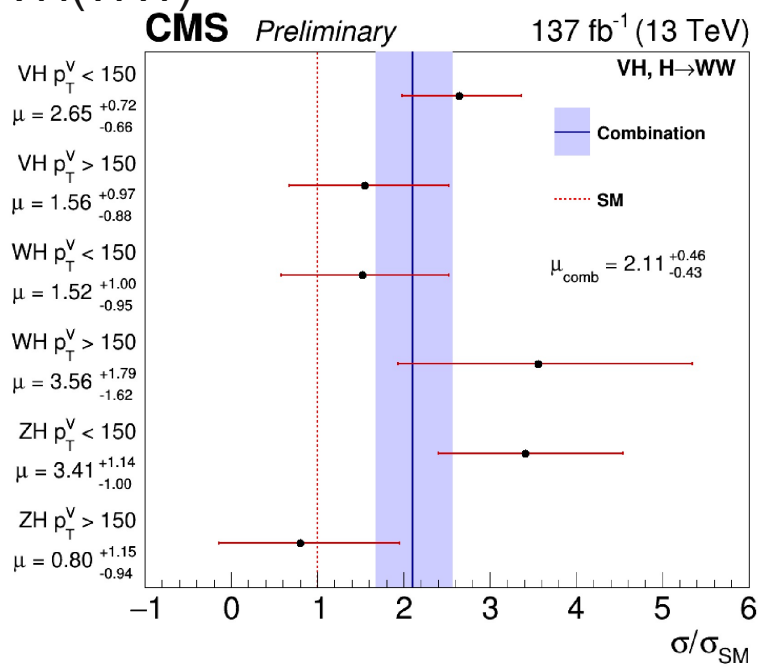
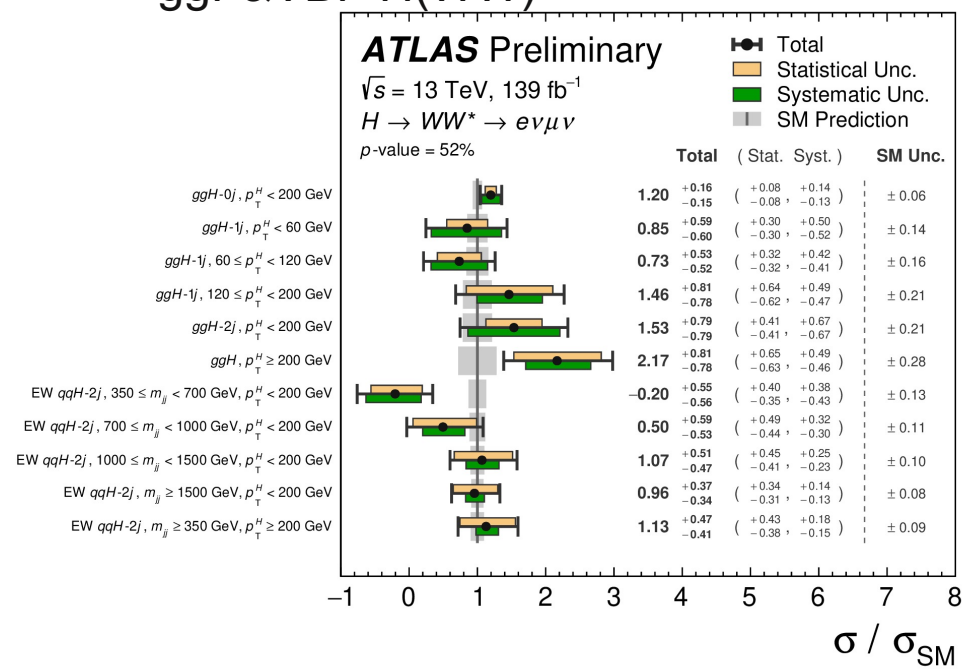
VH(WW)



ggF&VBF H(WW)



VH(WW) significance: 4.9(2.7)σ obs.(exp.)

HIG-19-017

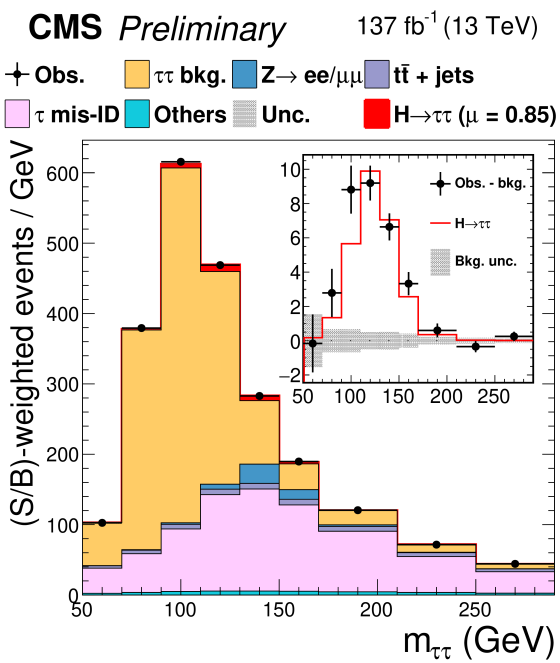
ATLAS-CONF-2021-014

…more details in V. Krisishnan's talk on Tue.

H→ττ Measurements

Challenge: reconstruction of τ decays due to ν in final states and jets being mis-identified as τ→hadrons decays

Run-2 data set enables STXS measurements in ggF and VBF



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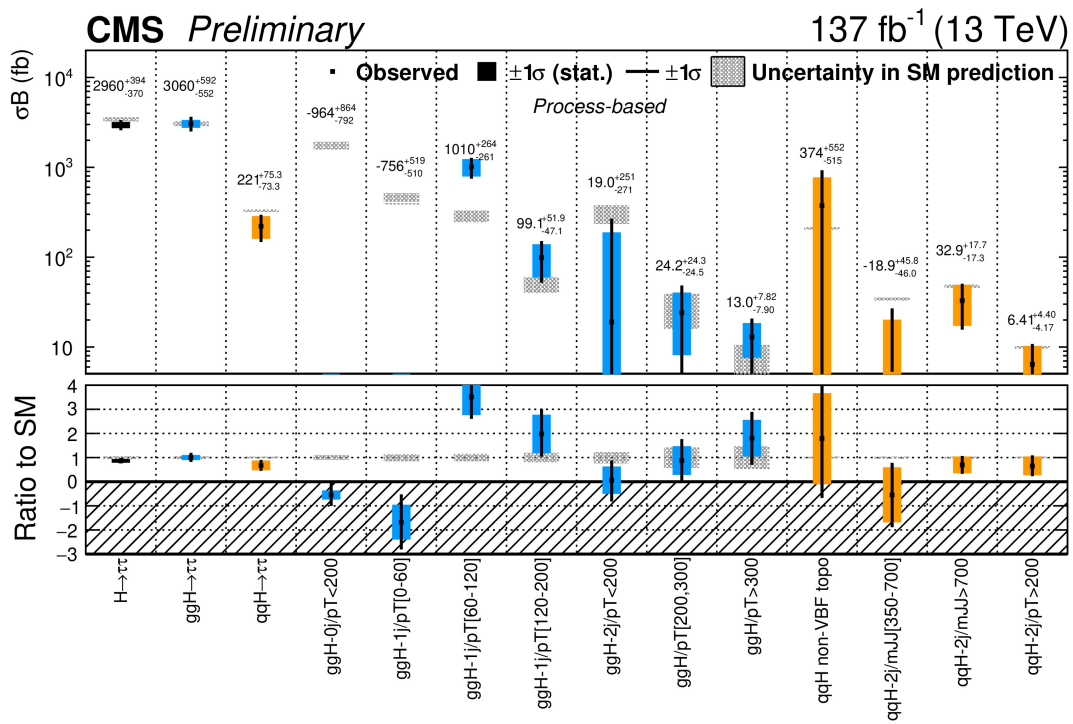

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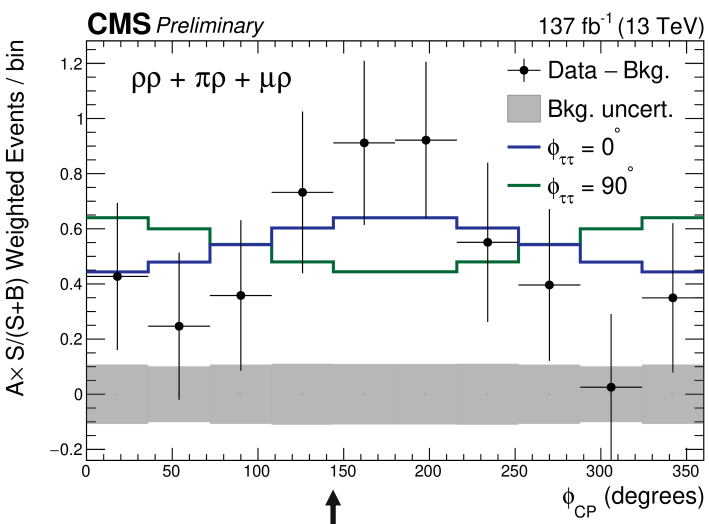

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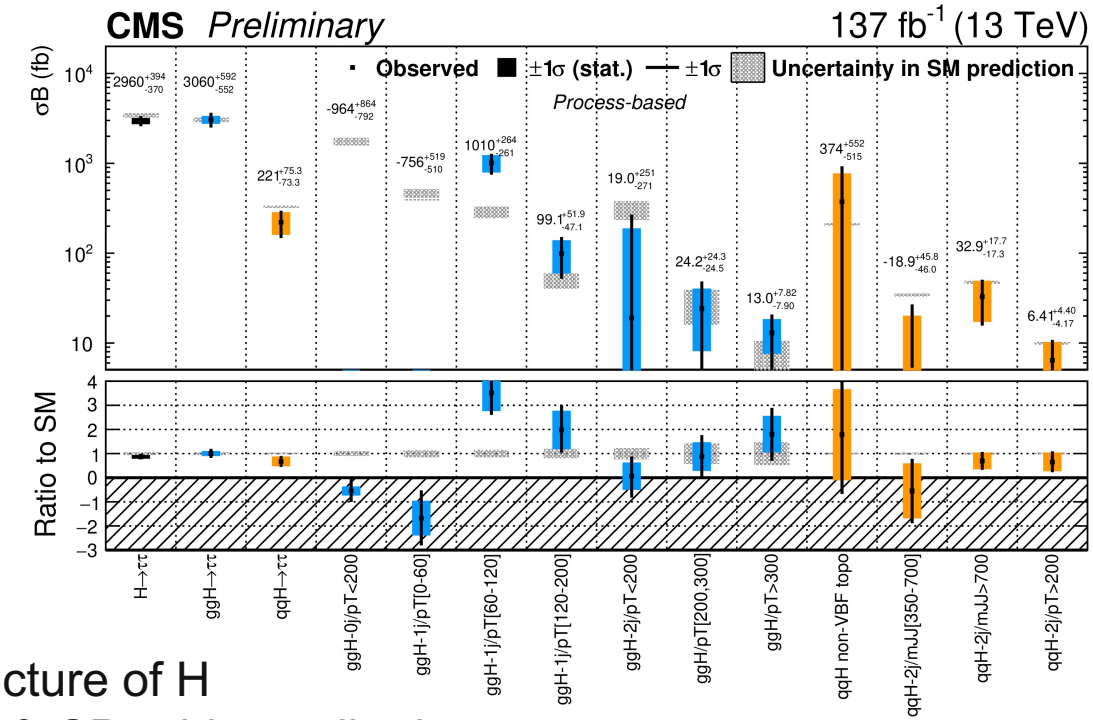
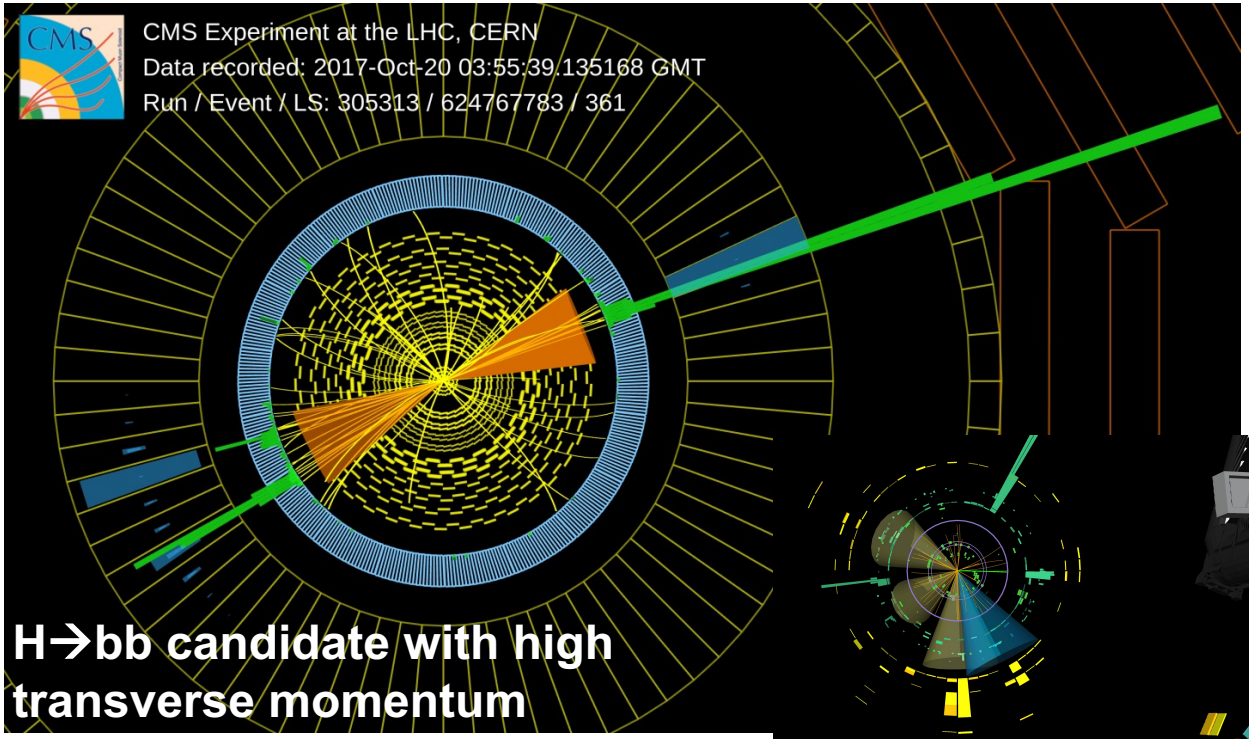


H→ττ decays sensitive to CP structure of H

mixing angle ϕ between CP-even & CP-odd contributions

ϕ = 4±36° at 95% CL

Higgs Candidate Events in Final States with Jets

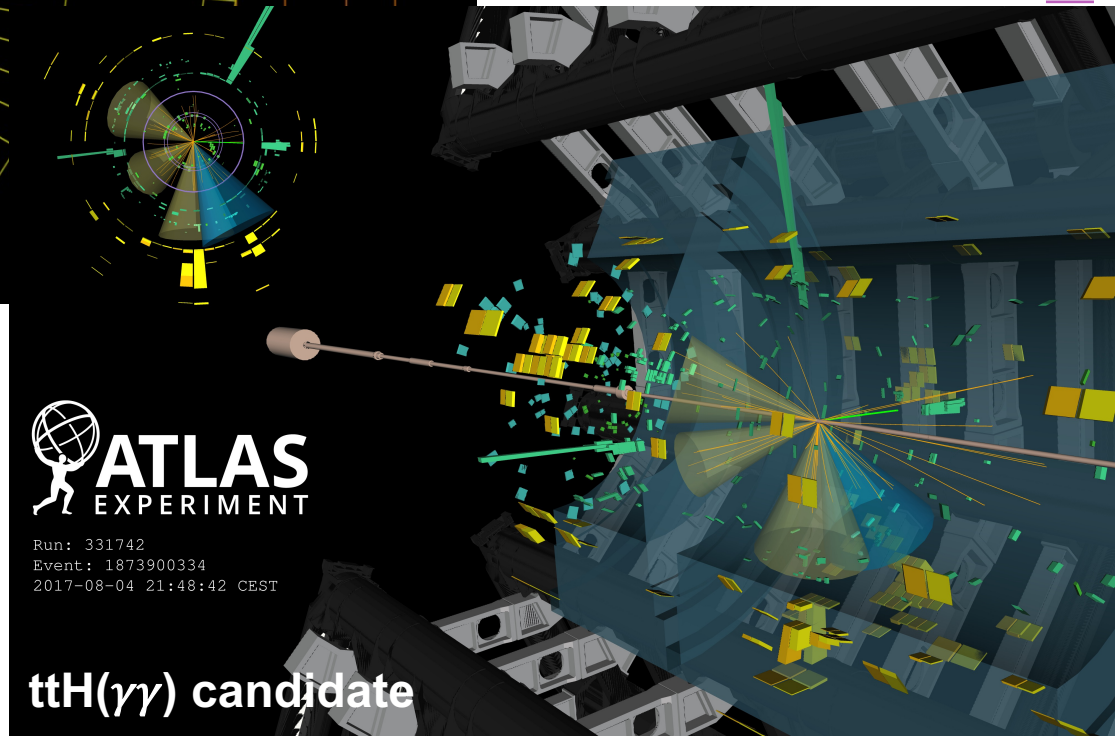


H→bb candidate with high transverse momentum

link

Displaced vertices and track impact parameter information allows to identify b-jets

link



ttH($\gamma\gamma$) candidate

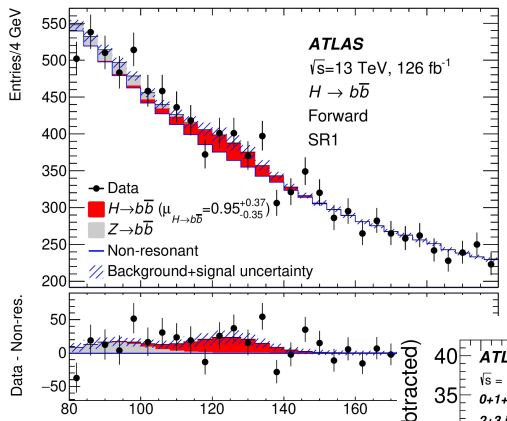
At high transverse momenta jets from H decays form one large jet with substructure

…more details in S.Hirose's talk on Tue.

H→bb Measurements

Highest SM BR (~60%) but massive amount of background events due to abundance of jet final states in pp-collisions

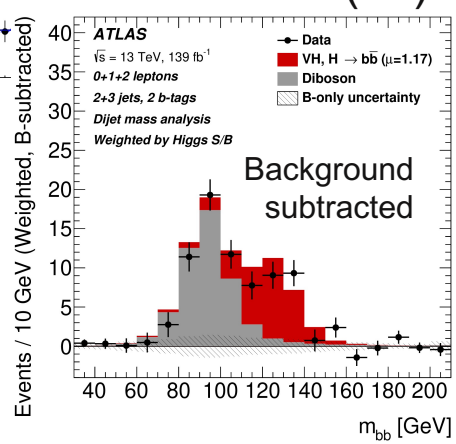
VH(bb): largest sensitivity due to background suppression in V→leptons channels



VBF H(bb)

arxiv:2011.08280

VH(bb)



VBF H(bb)	WH(bb)	ZH(bb)	Observed significances
2.9 σ	4.0 σ	5.3 σ	

…more details in S.Hirose's talk on Tue.

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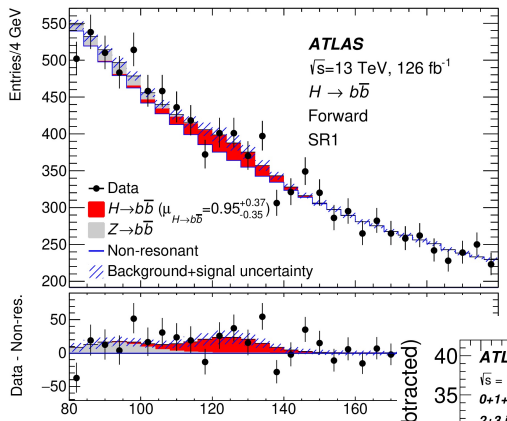
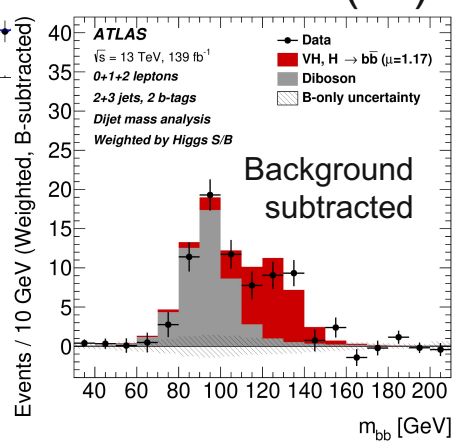


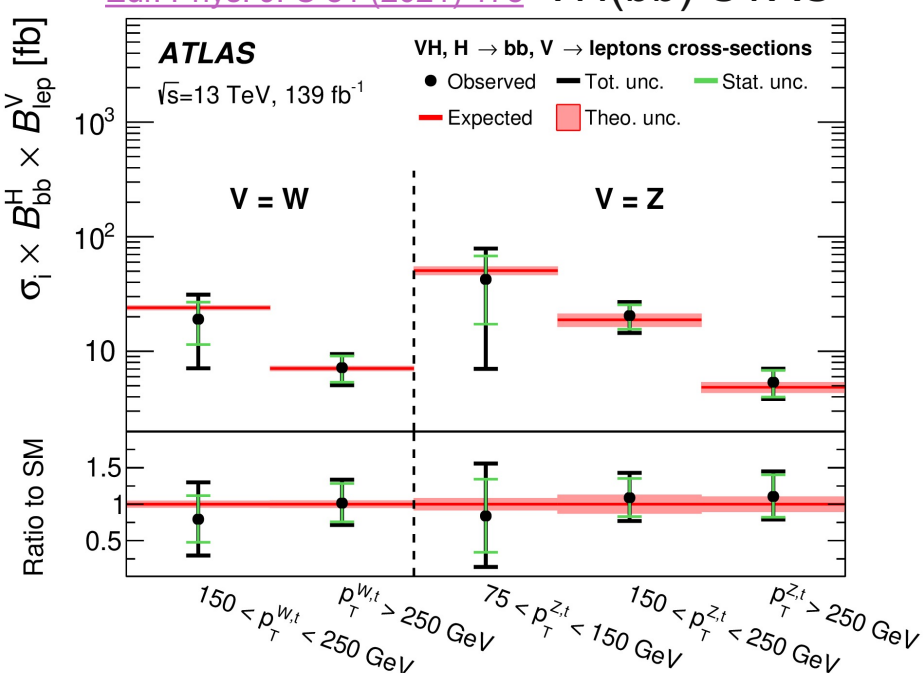
VBF H(bb)

arxiv:2011.08280

VH(bb)



Eur. Phys. J. C 81 (2021) 178 VH(bb) STXS



VBF H(bb)	WH(bb)	ZH(bb)
2.9 σ	4.0 σ	5.3 σ

Observed significances

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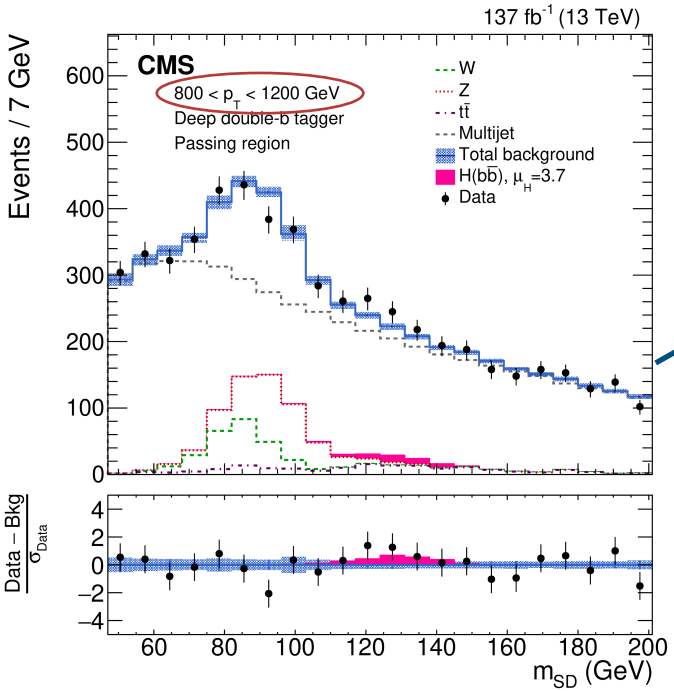
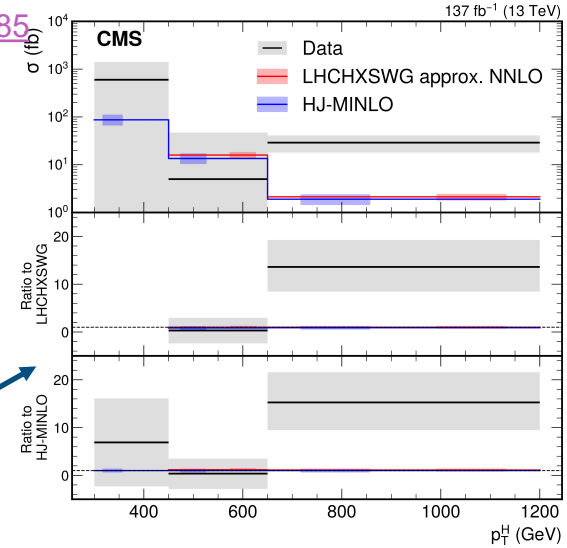
…more details in S.Hirose's talk on Tue.

H→bb at High p_T

Unique opportunity to probe extreme p_T due to large BR

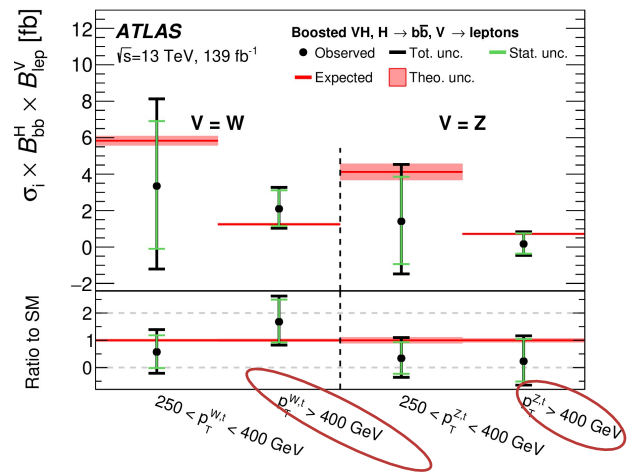
inclusive H→bb JHEP 12 (2020) 085

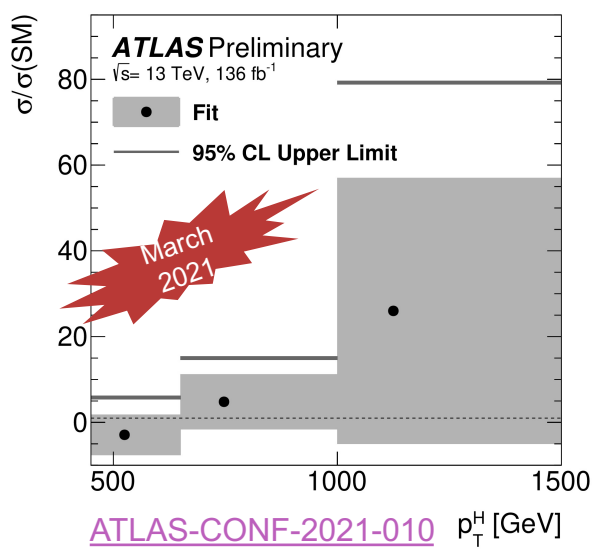




Phys. Lett. B 816 (2021) 136204

Boosted **VH(bb)**





Probe up to TeV scale in fully hadronic inclusive H→bb channel
→ Large statistical uncertainties at extreme p_T

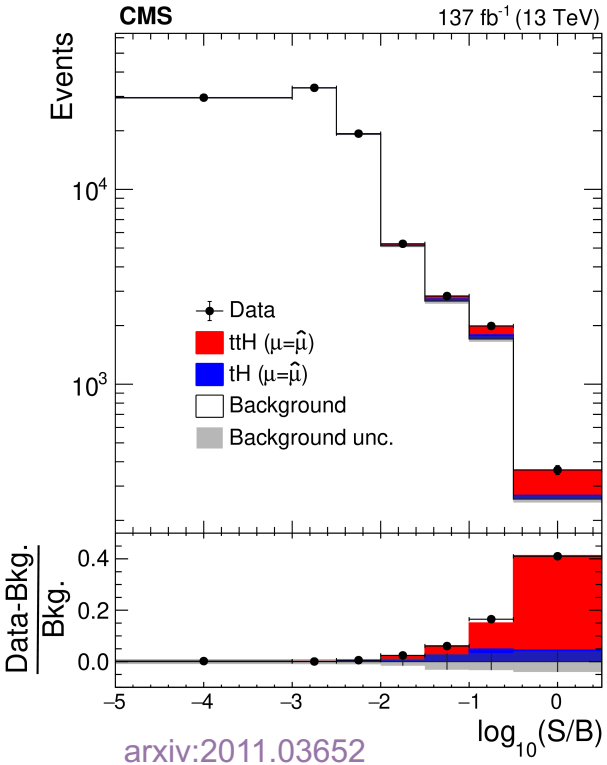
ATLAS-CONF-2021-010

…more details in S.Hirose's talk on Tue.

Higgs-Top Couplings

ttH production probes H Yukawa couplings at high masses
Challenge: small cross sections, many final state particles and background processes with large theory uncertainties

Multi-lepton final states



arxiv:2011.03652

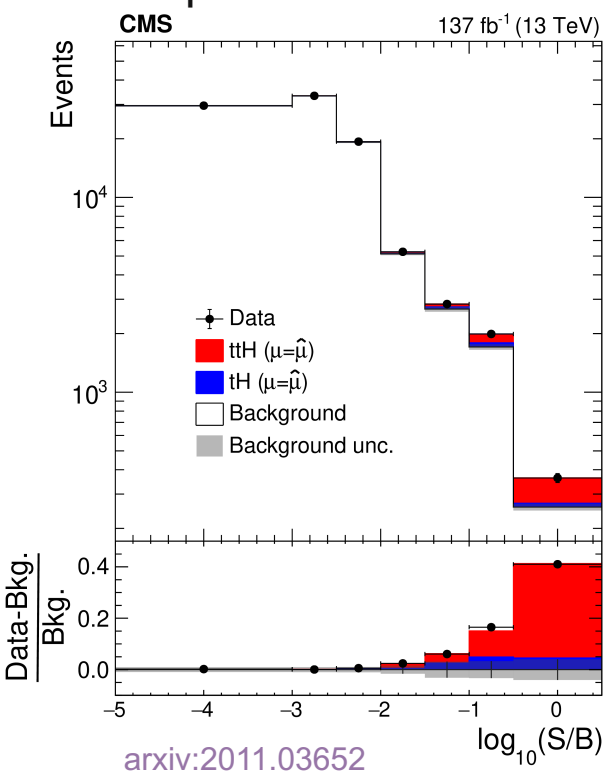
ttH in multi-lepton final states (H→WW, H→$\tau\tau$, H→ZZ) measurement (CMS):
4.7σ observed significance
$\mu_{ttH} = 0.92 \pm 0.19(\text{stat.})^{+0.17}_{-0.13}(\text{syst.})$

…more details in S.Hirose's talk on Tue.

Higgs-Top Couplings

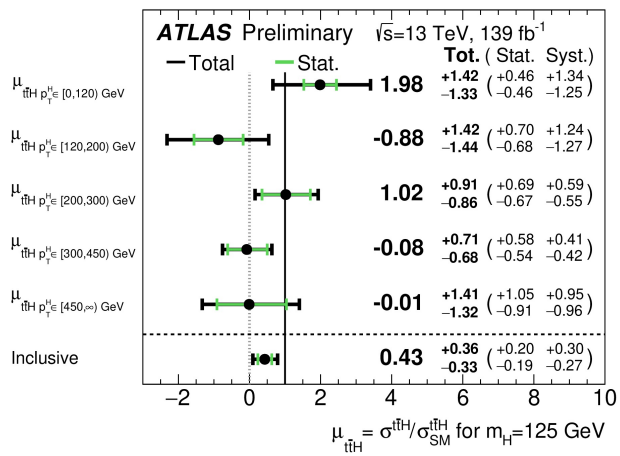
ttH production probes H Yukawa couplings at high masses
Challenge: small cross sections, many final state particles and background processes with large theory uncertainties

Multi-lepton final states



arxiv:2011.03652

STXS in ttH(bb)



ATLAS-CONF-2020-058

ttH in multi-lepton final states (H→WW, H→$\tau\tau$, H→ZZ) measurement (CMS):
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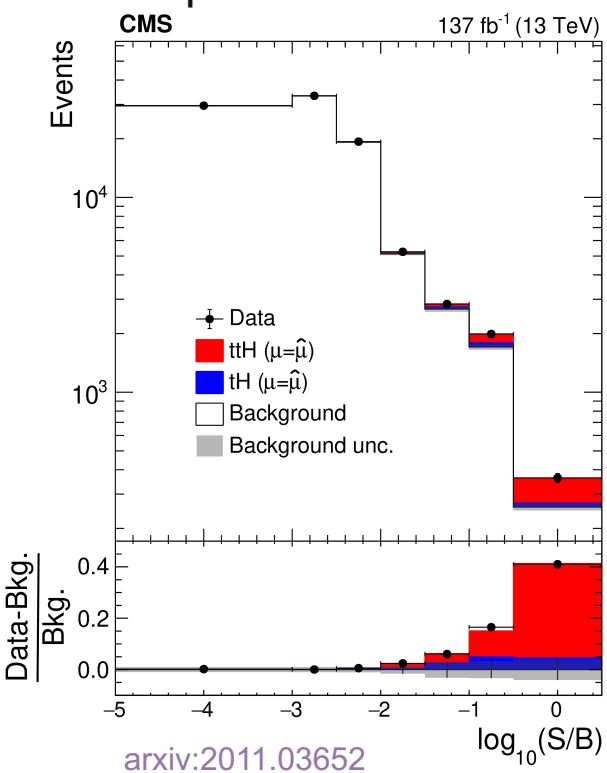
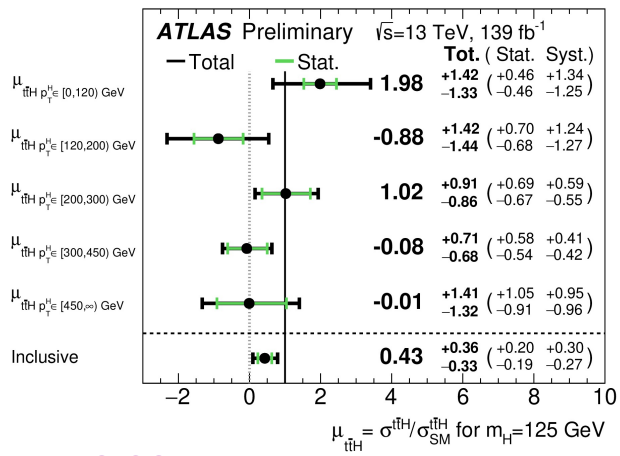


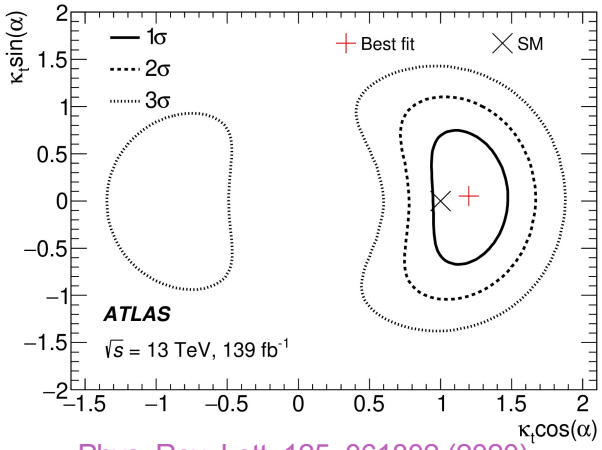
arxiv:2011.03652

STXS in ttH(bb)



ATLAS-CONF-2020-058

CP structure in ttH($\gamma\gamma$)



Phys. Rev. Lett. 125, 061802 (2020)

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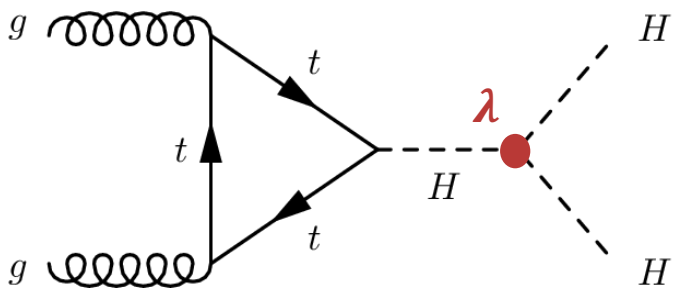
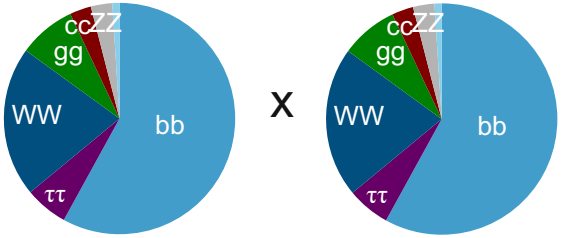
$$\mu_{ttH} = 0.92 \pm 0.19(\text{stat.})^{+0.17}_{-0.13}(\text{syst.})$$

Di-Higgs Production

Direct access to Higgs self-coupling strength (λ), which probes shape of the Higgs potential

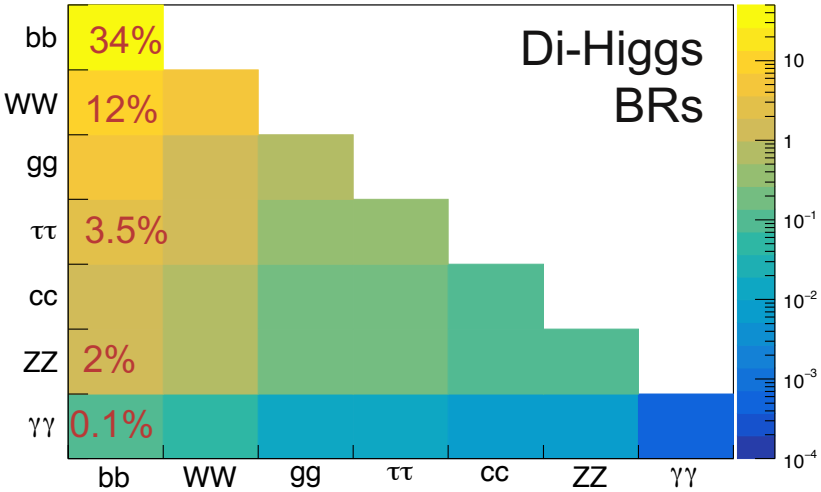
Small SM cross sections → Reaches full potential at HL-LHC



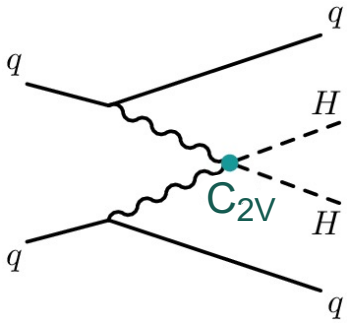


=

Careful balance of "high resolution" decay channels and BRs

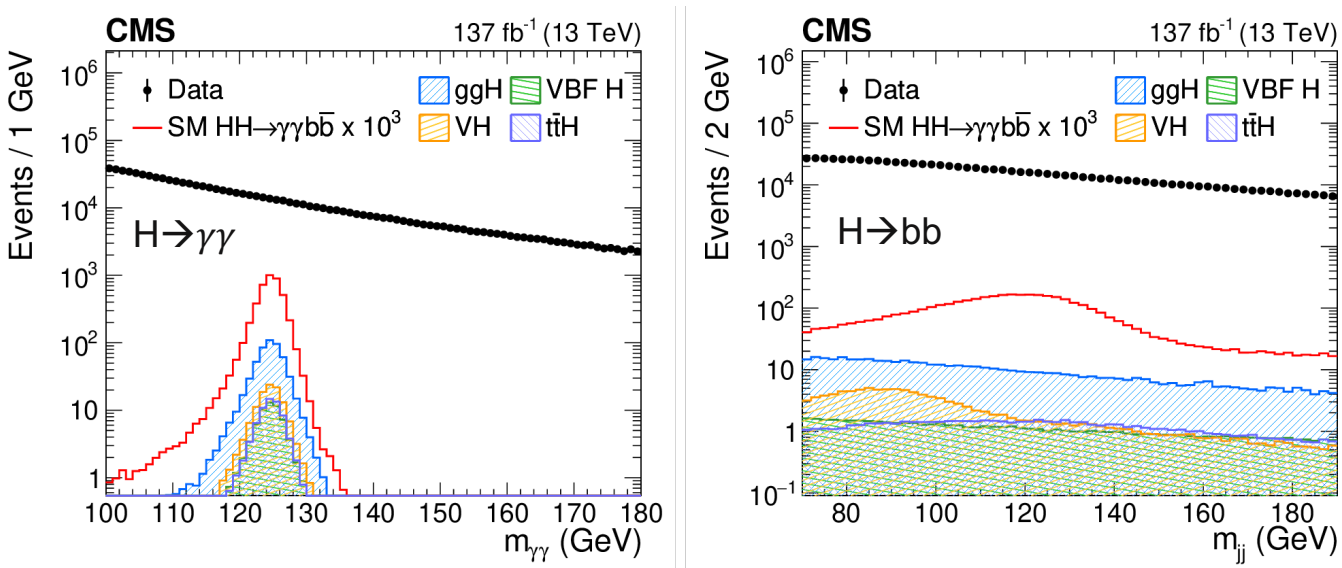


VBF production probes HHVV coupling



HH→$\gamma\gamma$bb Measurements

Channel with (current) highest sensitivity to SM HH production
→ Large improvements in sensitivity for full Run-2 analysis using machine learning

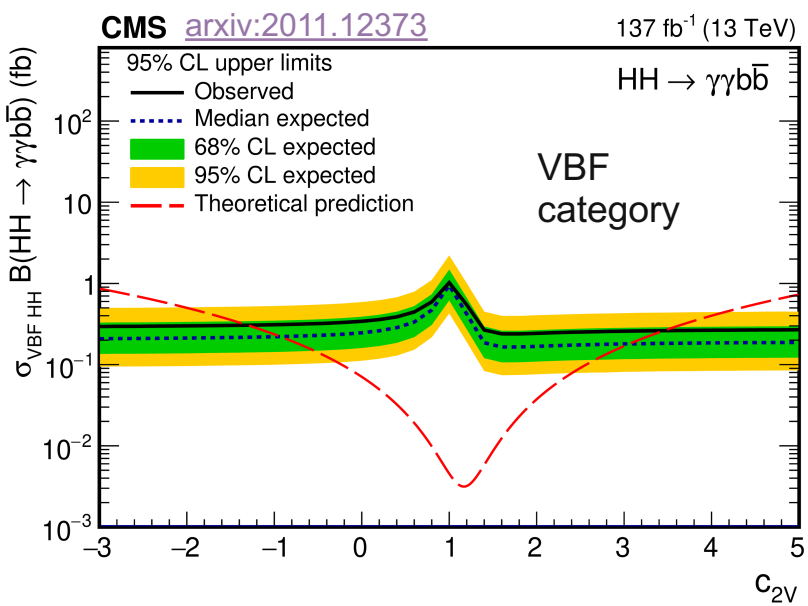


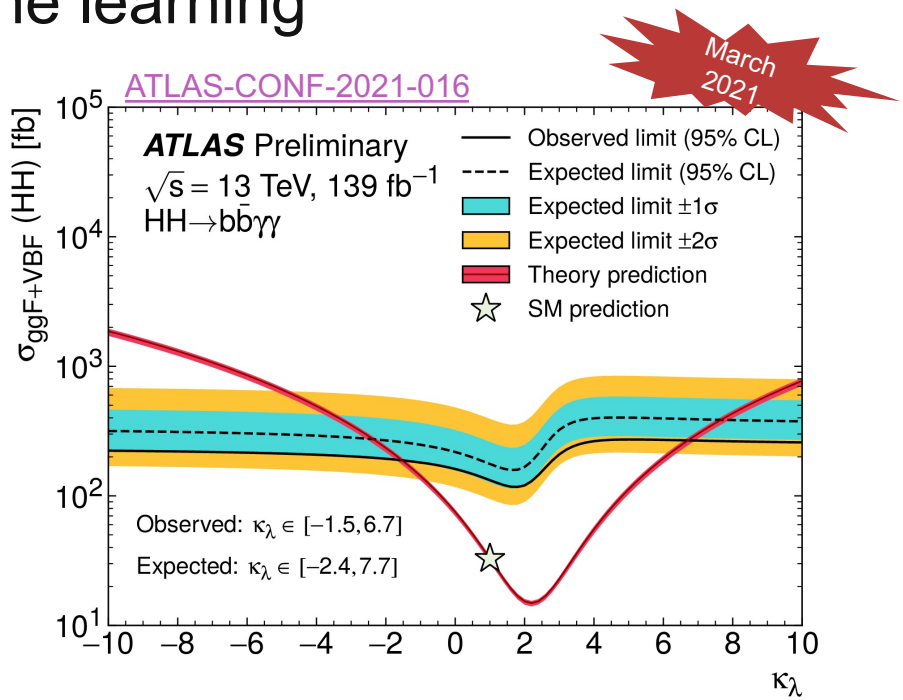
→No significant fluctuation over background
→Set limits on SM σ(pp→HH)*BR(HH→ $\gamma\gamma$bb)
→Scan full range of $m_{\gamma\gamma bb}$ for X→HH resonances

…more details in L. D'Eramo's talk on Thu.

HH→$\gamma\gamma$bb Measurements

Channel with (current) highest sensitivity to SM HH production
→ Large improvements in sensitivity for full Run-2 analysis using machine learning





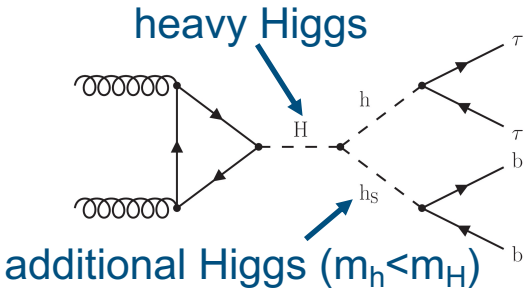
CMS 95% CL limits:
$\sigma \cdot \mathrm{BR} < 7.7 \times \mathrm{SM\ expectation}$
$-3.3 < \kappa_\lambda < 8.5$
$-1.3 < c_{2V} < 3.5$

ATLAS 95% CL limits:
$\sigma \cdot \mathrm{BR} < 4.1 \times \mathrm{SM\ expectation}$
$-1.5 < \kappa_\lambda < 6.7$

ATLAS VBF HH→4b: $-0.43 < c_{2V} < 2.56$
arxiv:2001.05178

…more details in J. Carter's talk on Wed.

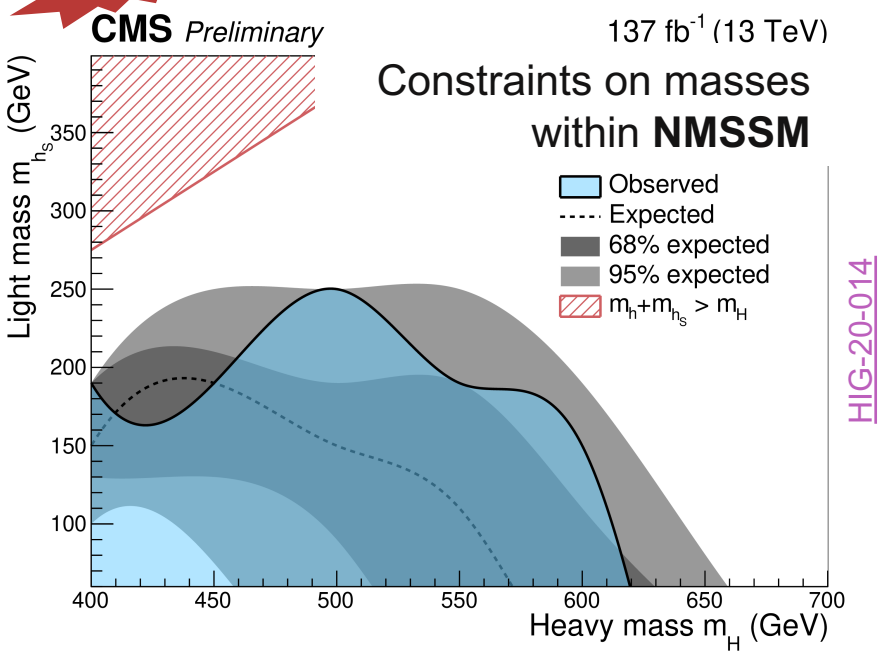
Heavy Higgs (H/A) Searches



Targeting decays to pairs of vector bosons and/or (B)SM Higgs bosons as part of extended H sector

March 2021

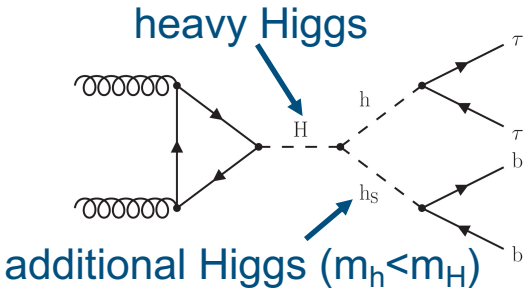
$H \rightarrow hh_s \rightarrow \tau\tau bb$



95% CL exclusion limits range:
from σ*BR<125 fb (low mass)
to σ*BR<2.7 fb (high mass)

…more details in J. Carter's talk on Wed.

Heavy Higgs (H/A) Searches



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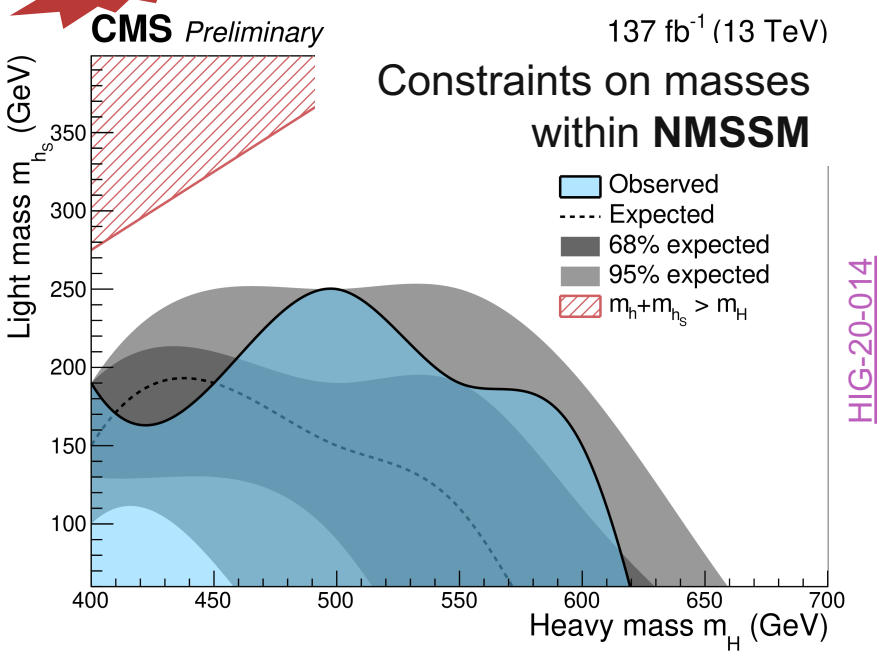
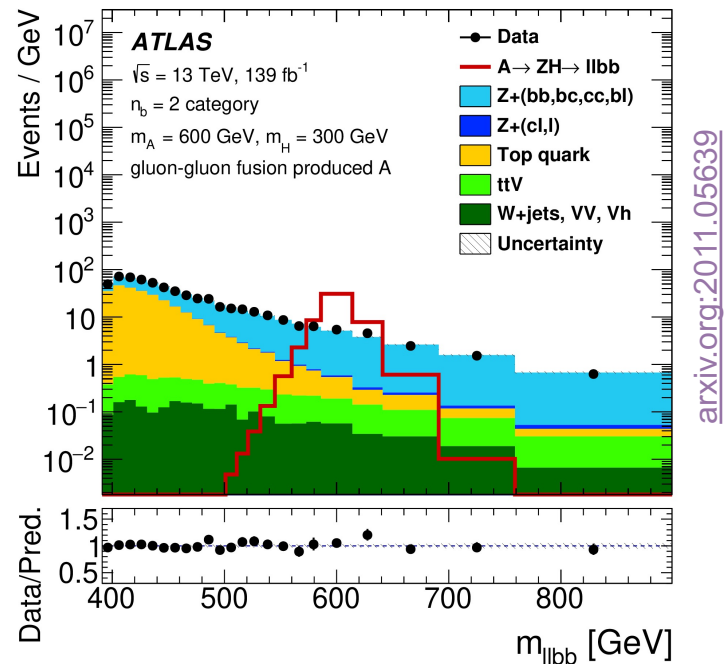


95% CL exclusion limits range:
from σ*BR<125 fb (low mass)
to σ*BR<2.7 fb (high mass)

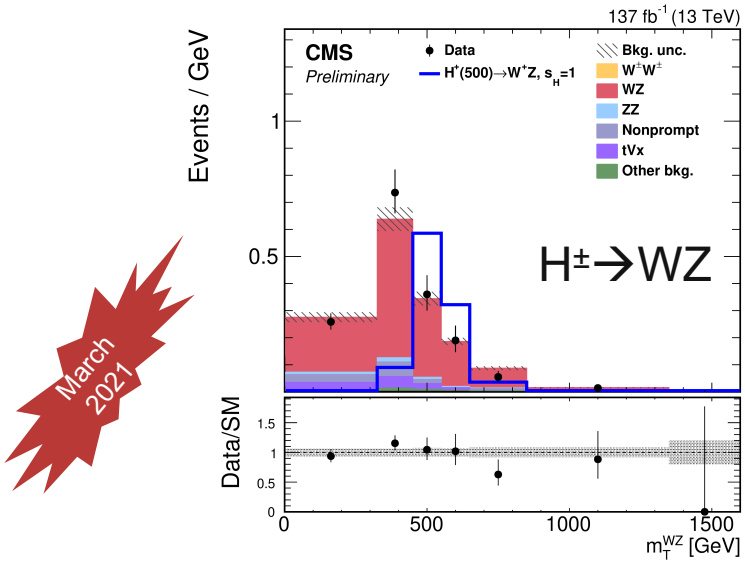
$A \rightarrow ZH \rightarrow \ell\ell bb/\ell\ell WW$



95% CL exclusion limits range:
from σ*BR<380 fb (low mass)
to σ*BR<6.2 fb (high mass)

…more details in J. Carter's talk on Wed.

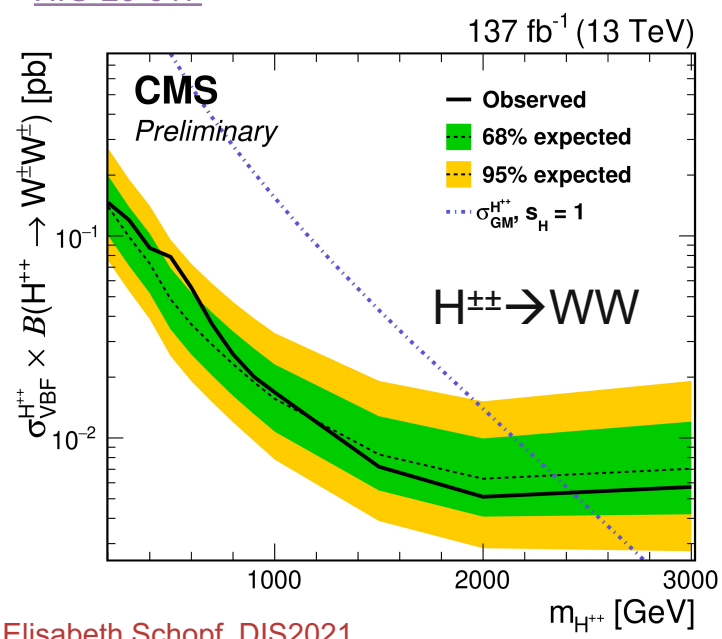
Heavy Charged Higgs



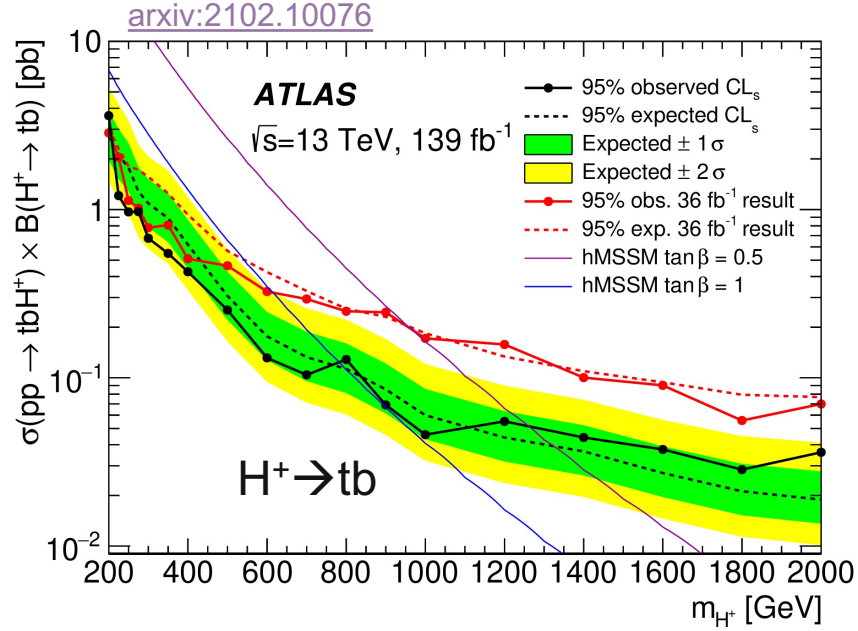
HIG-20-017

Charged Higgs Boson as part of extended Higgs sector predicted in several BSM models

Searches span singly and doubly charged Higgs bosons → recent ATLAS search also probes pair production of charged H: arxiv:2101.11961



arxiv:2102.10076



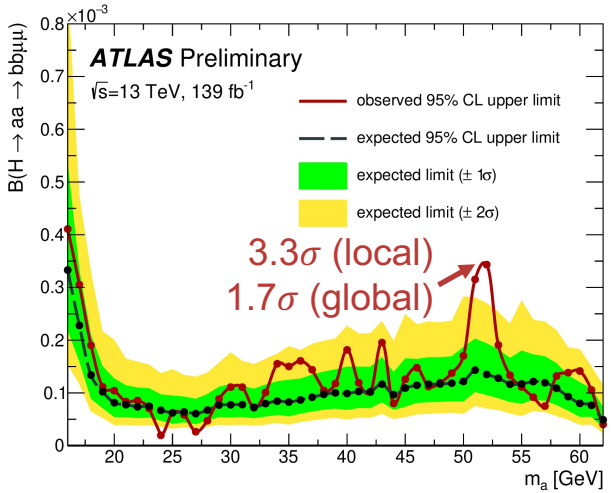
…more details in A. Leopold's talk on Wed.

Exotic Higgs Decays

Target new undiscovered particles that couple to SM Higgs

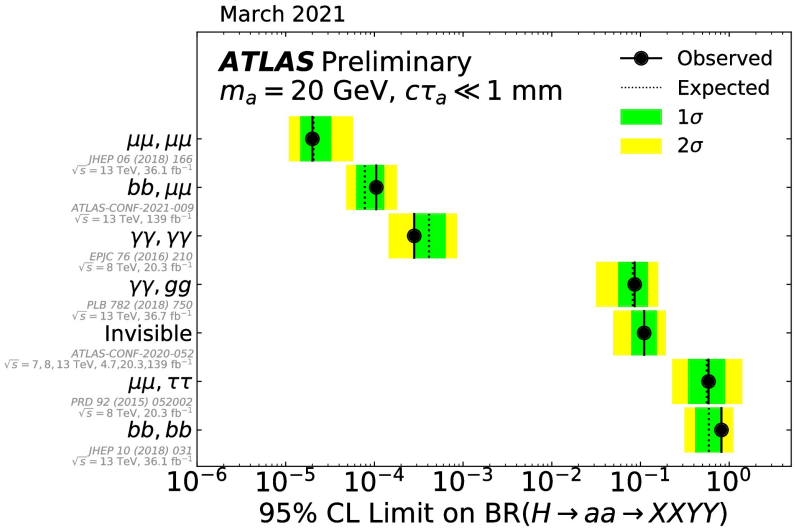
H→aa→bb$\mu\mu$ (a=spin 0)

ATLAS-CONF-2021-009



March 2021

Summary of H→aa searches



ATL-PHYS-PUB-2021-008

…more details in A. Leopold's talk on Wed.

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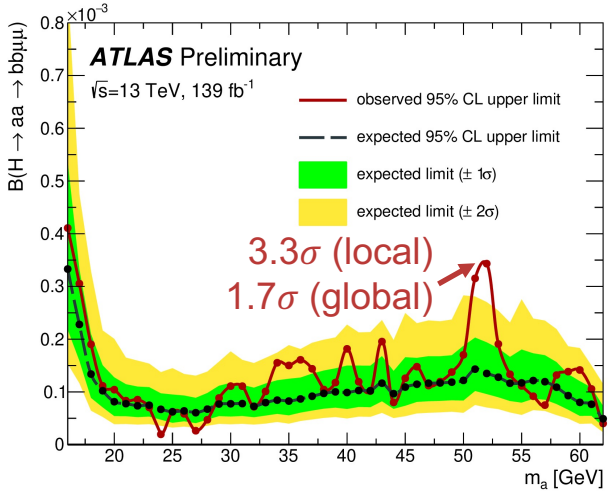
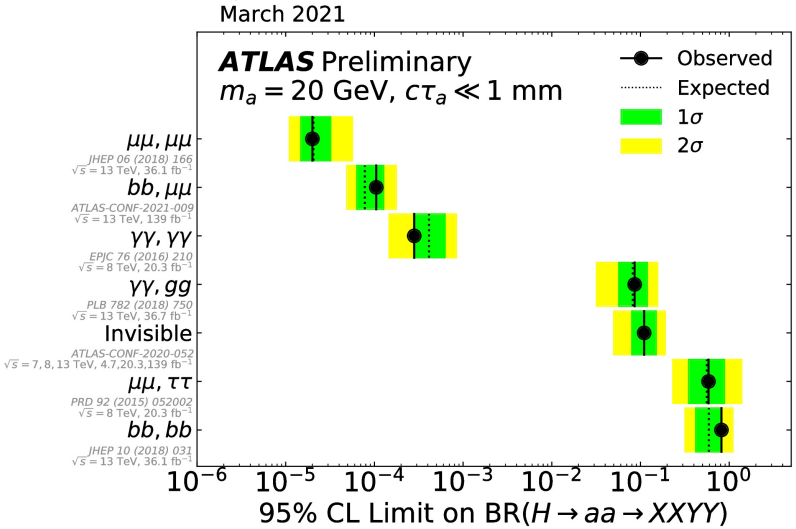
ATLAS-CONF-2021-009



March 2021

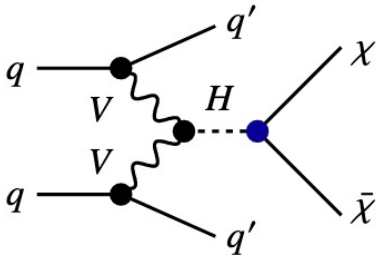
Summary of H→aa searches

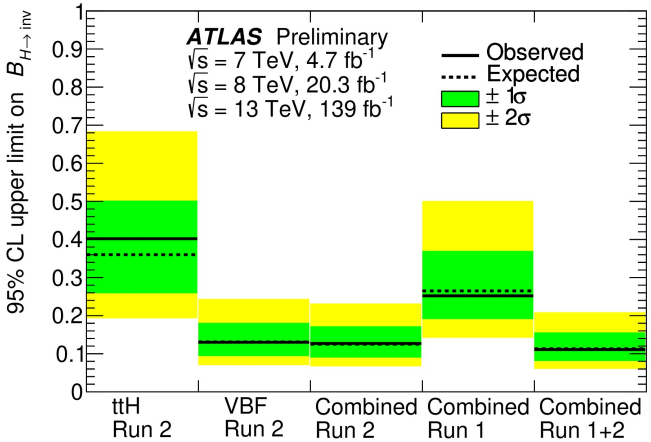
March 2021



ATL-PHYS-PUB-2021-008

H → Dark Matter





ATLAS: ATLAS-CONF-2020-052
BR(H→invisible) < 11% at 95% CL

CMS ZH(invisible) Run-2:
BR(H→invisible) < 25% at 95% CL

Eur. Phys. J. C 81 (2021) 13

Summary

- LHC Run-2: excellent data-sets for Higgs boson physics in ATLAS and CMS
- **Unprecedented precision**
  - Measurement of Higgs mass/CP, differential distributions/STXS
  - Evidence for rare decays
  - Pushing limits on SM HH
- Vast programme of **BSM searches** in the Higgs sector
- (so far) Everything **consistent with SM**
- We expect **much more data to come** during LHC Run-3 and HL-LHC operations → **Stay tuned!**

Thank you for your attention!

For more details and exciting LHC Higgs results at DIS2021 check out the talks referenced in the various slides as well as:

Where do we go from here? →

"Future Physics Prospects with the CMS Detector at the High-Luminosity LHC" – CONOR HENDERSON

"Prospects for Higgs and di-Higgs measurements at the ATLAS experiment" – ALESSANDRA BETTI

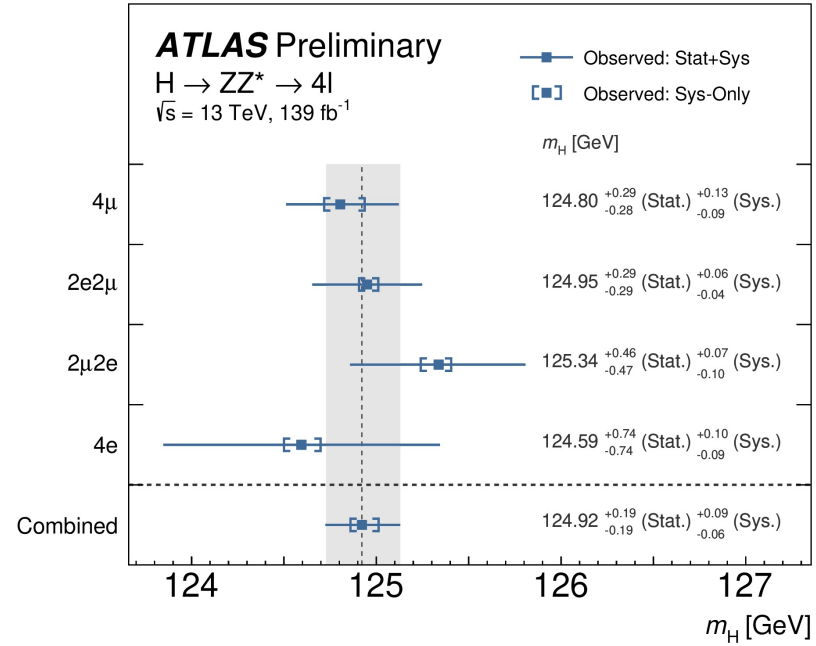
"Higgs physics at the LHeC and the FCC-eh" – UTA KLEIN

"Prospects for Higgs Physics at the HL-LHC" - CORRINNE MILLS

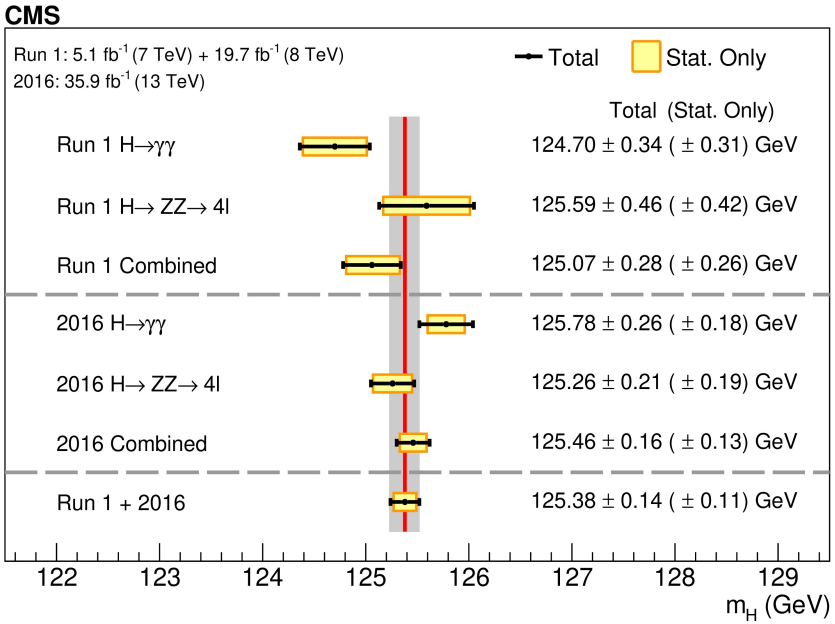
Higgs Boson Mass

Measurement broken down into each analysis channel

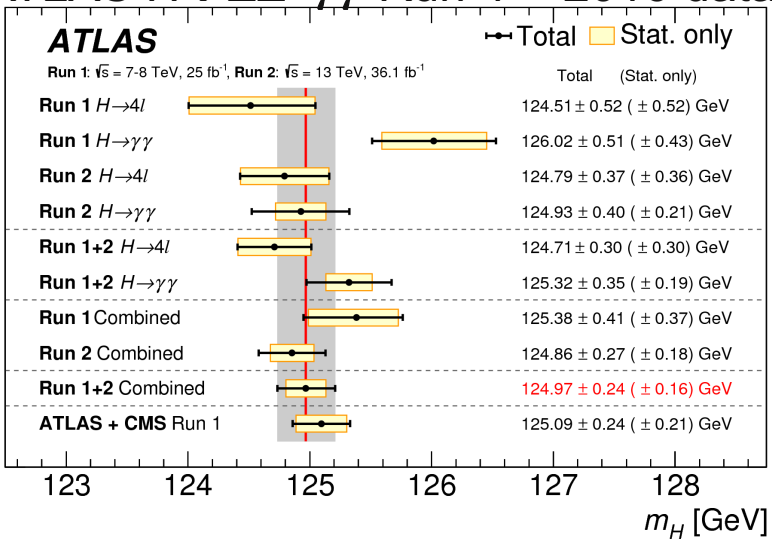
ATLAS H→ZZ full Run-2



CMS H→ZZ+$\gamma\gamma$ Run-1 + 2016 data



ATLAS H→ZZ+$\gamma\gamma$ Run-1 + 2016 data



HIG-19-004

ATLAS-CONF-2020-005

arxiv:1806.00242

Higgs Boson Mass: Uncertainties

HIG-19-004

ATLAS-CONF-2020-005

ATLAS H→ZZ full Run-2

Systematic Uncertainty	Impact (GeV)
Muon momentum scale	+0.08,−0.06
Electron energy scale	±0.02
Muon momentum resolution	±0.01
Muon sagitta bias correction	±0.01

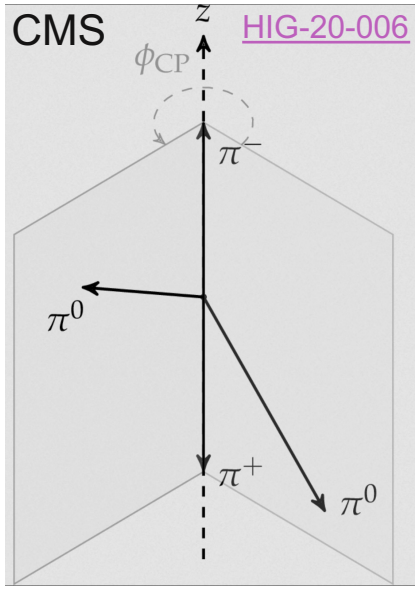
CMS H→ZZ+$\gamma\gamma$ Run-1 + 2016 data

Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

CP Structure

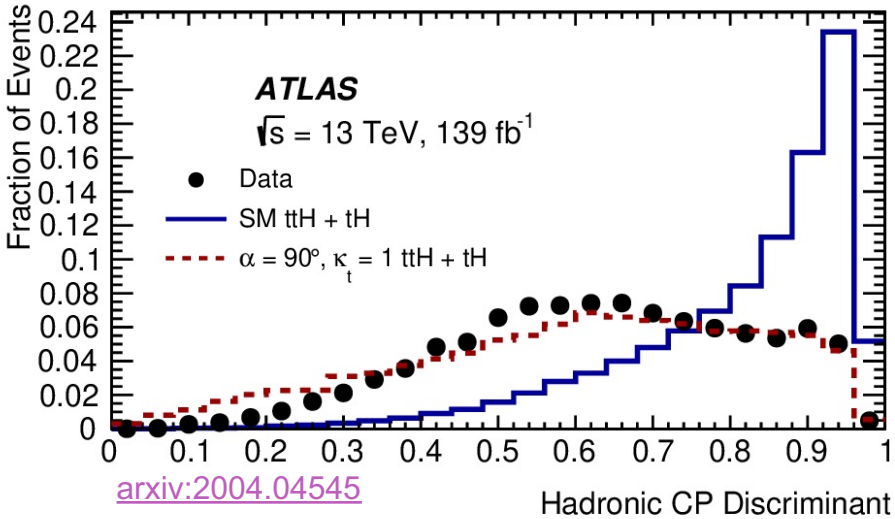
tH/ttH($\gamma\gamma$): mixing angles >43º excluded at 95% CL (ATLAS)

H→$\tau\tau$: mixing angle =4±36º at 95% CL (CMS)



Decay planes in $\tau\tau$→pions decays

NB: data dominated by background events!

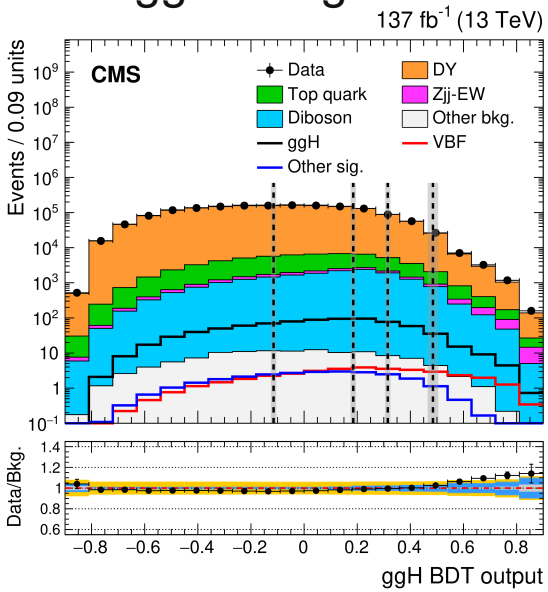


arxiv:2004.04545

Purely CP-odd H already excluded but admixtures still possible

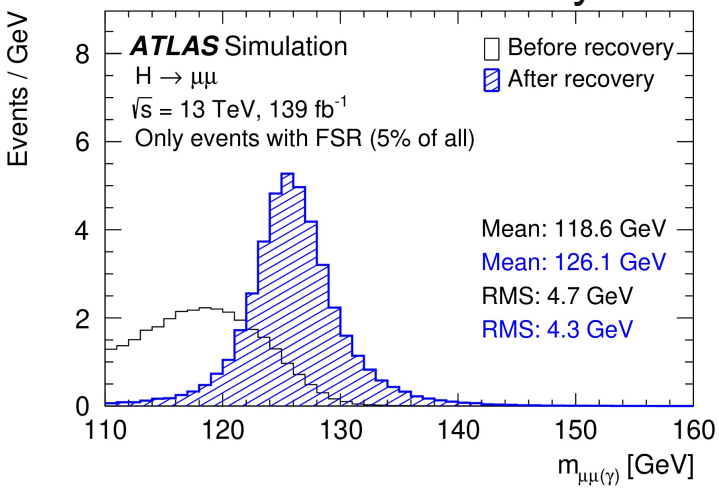
H→$\mu\mu$ additional information

CMS ggF categorization BDT



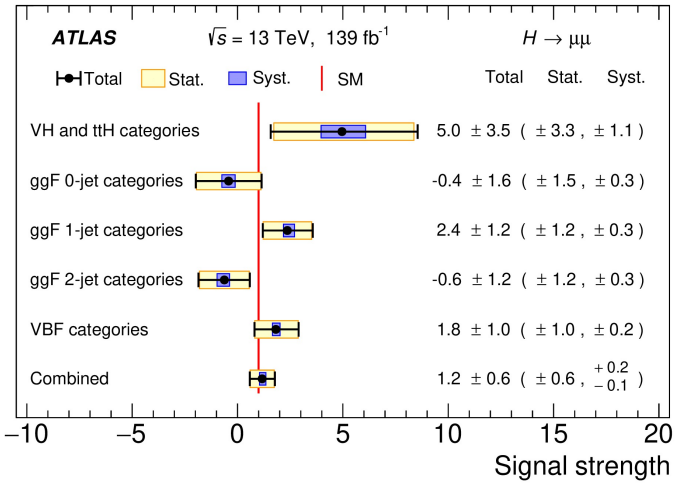
Machine learning categorization used in ATLAS as well

ATLAS FSR recovery



Similar BDTs used in VH and ttH

ATLAS results per channel



CMS sensitivity per channel

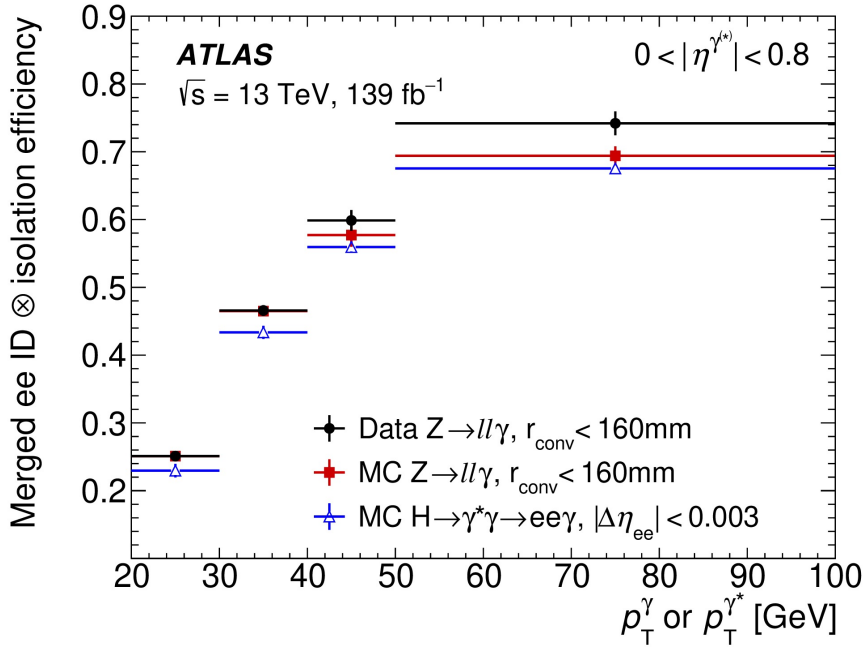
Production category	Observed (expected) signif.	Observed (expected) UL on μ
VBF	2.40 (1.77)	2.57 (1.22)
ggH	0.99 (1.56)	1.77 (1.28)
ttH	1.20 (0.54)	6.48 (4.20)
VH	2.02 (0.42)	10.8 (5.13)
Combined $\sqrt{s} = 13$ TeV	2.95 (2.46)	1.94 (0.82)
Combined $\sqrt{s} = 7,\ 8,\ 13$ TeV	2.98 (2.48)	1.93 (0.81)

H→$\ell\ell\gamma$ additional information

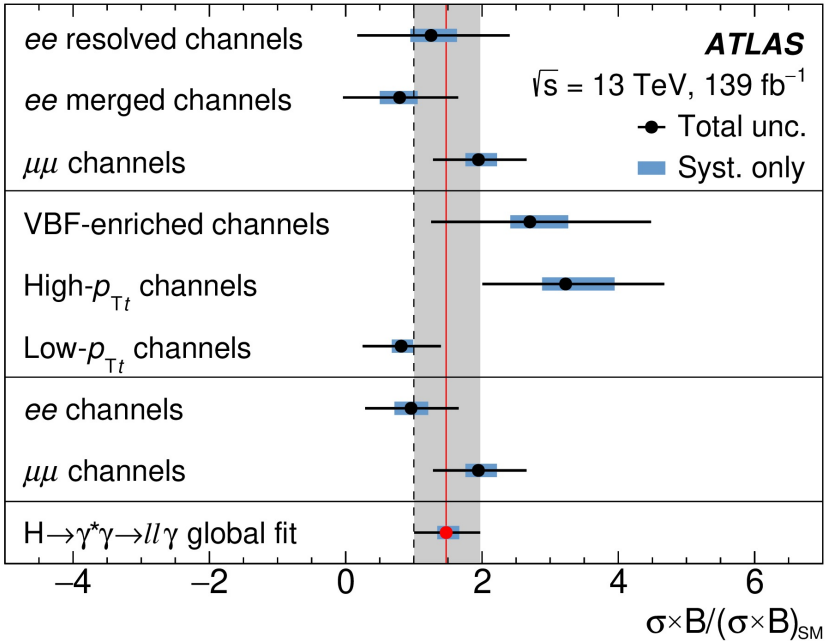
arxiv:2103.10322

Multivariate discriminator to distinguish merged γ→ee from single electrons and jets using shower shape, track, kinematic information as well as information from the transition radiation tracker

Selection efficiency for merged γ→ee candidates

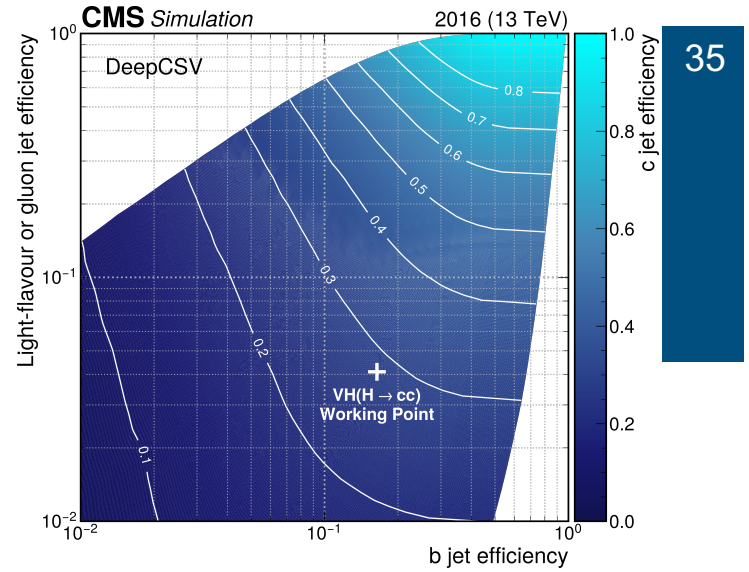


Result per analysis channel



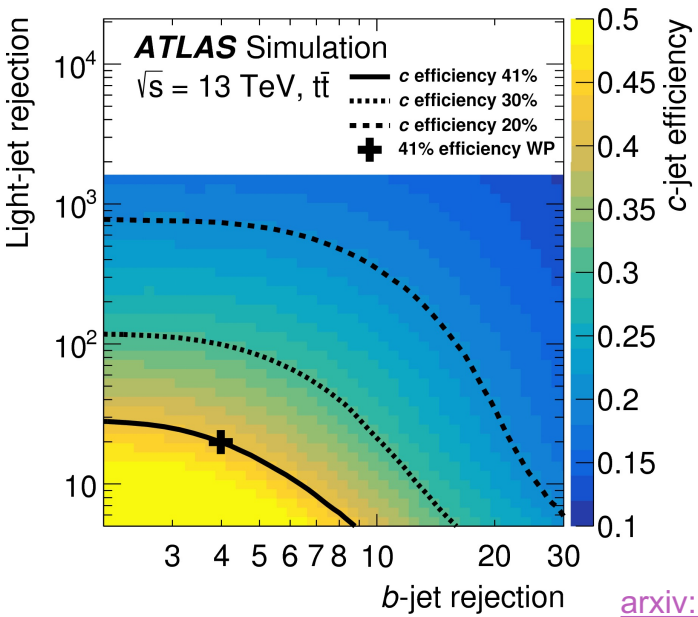
H→cc Searches

Searches with partial Run-2 data (2015+2016)
Target VH production
Challenge: ID c-jets



CMS c-jet tagging efficiency

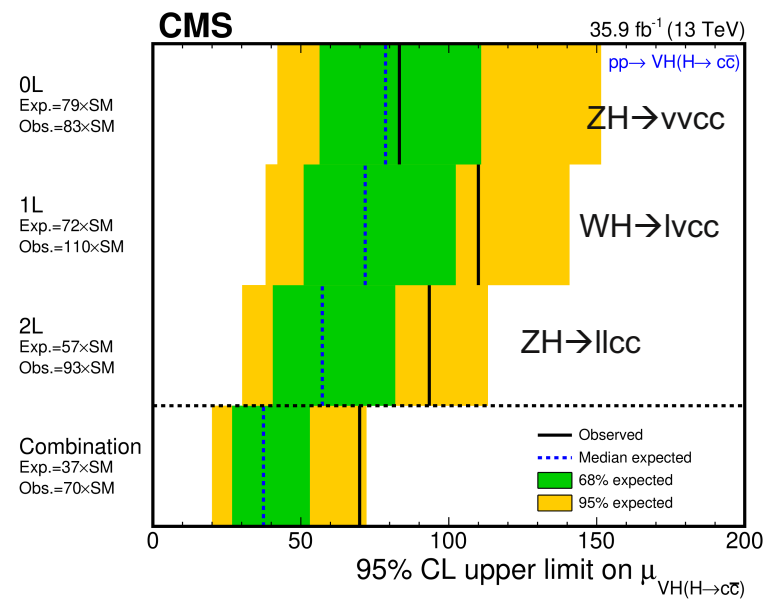
ATLAS c-jet tagging efficiency



arxiv:1802.04329

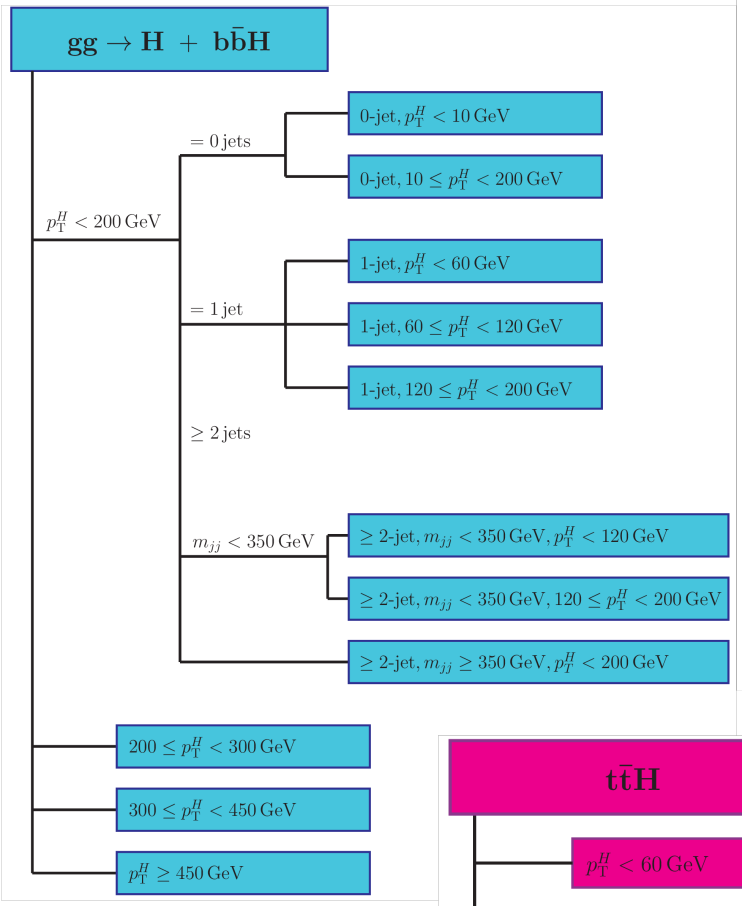
arxiv:1912.01662

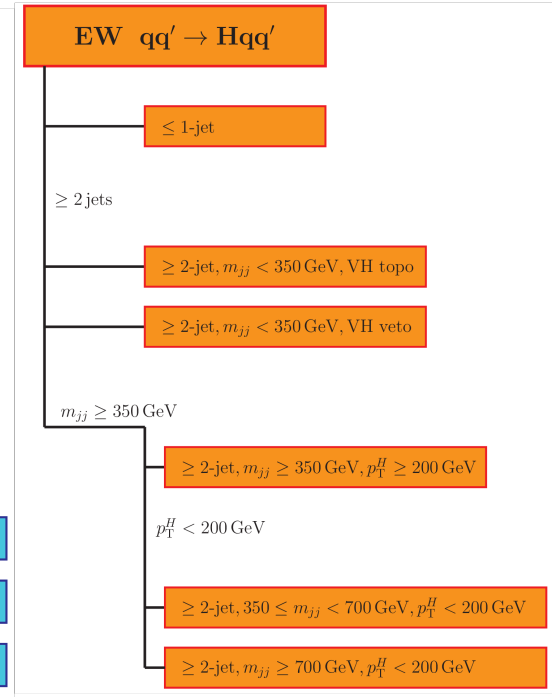
CMS results

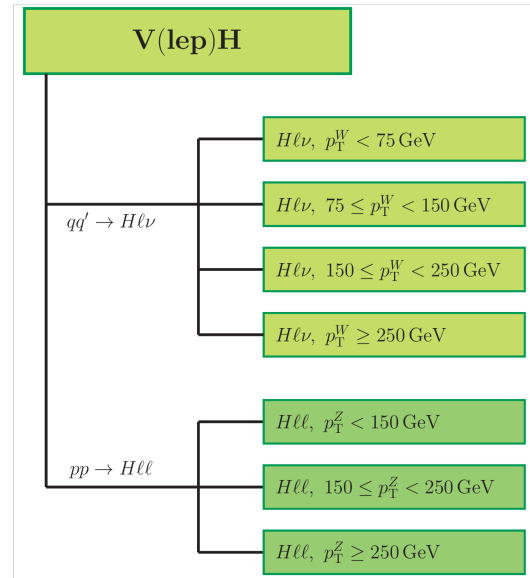


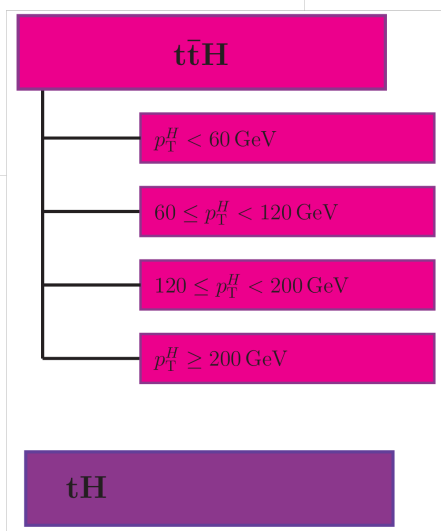
ATLAS 95% CL limits:
$\sigma(pp \to ZH) * BR(ZH \to \ell\ell cc) < 110$ SM expectation

STXS Categories









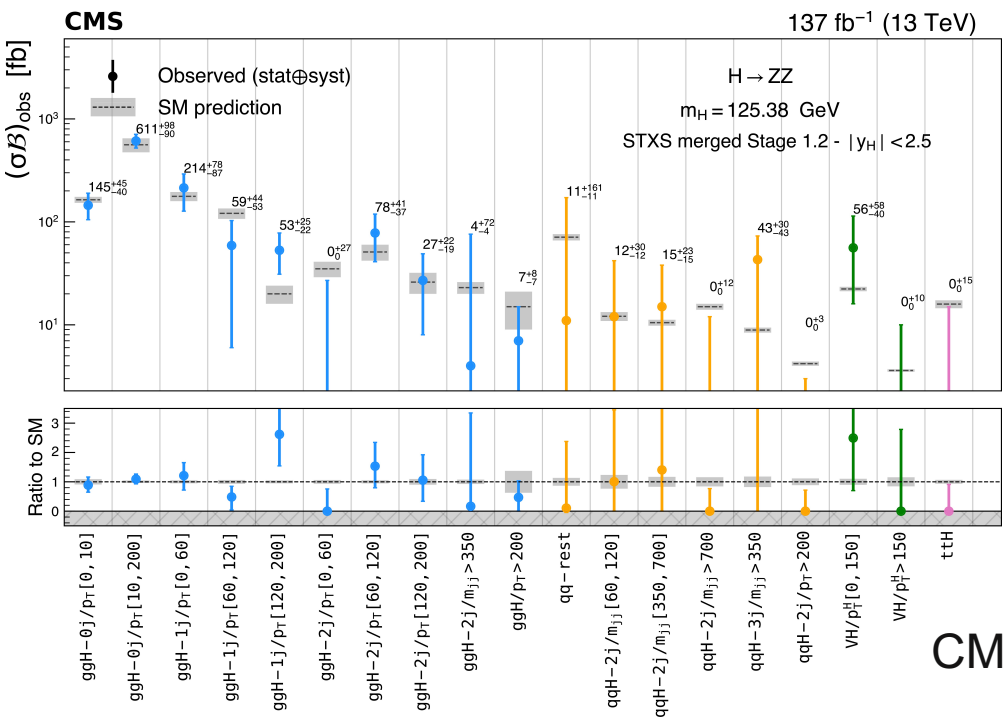
Categorisation for STXS measurements in various Higgs production channels

Differential Distributions additional information

arxiv:2103.04956
arxiv:2004.03969

Higgs boson kinematic-related variables	
$p_T^{4\ell}$, $\lvert y_{4\ell}\rvert$	Transverse momentum and rapidity of the four-lepton system
m_{12}, m_{34}	Invariant mass of the leading and subleading lepton pair
$\lvert\cos\theta^*\rvert$	Magnitude of the cosine of the decay angle of the leading lepton pair in the four-lepton rest frame relative to the beam axis
$\cos\theta_1$, $\cos\theta_2$	Production angles of the anti-leptons from the two Z bosons, where the angle is relative to the Z vector.
ϕ, ϕ_1	Two azimuthal angles between the three planes constructed from the Z bosons and leptons in the Higgs boson rest frame.
Jet-related variables	
N_{jets}, $N_{b\text{-jets}}$	Jet and b-jet multiplicity
$p_T^{\text{lead. jet}}$, $p_T^{\text{sublead. jet}}$	Transverse momentum of the leading and subleading jet, for events with at least one and two jets, respectively. Here, the leading jet refers to the jet with the highest p_T in the event, while subleading refers to the jet with the second-highest p_T.
m_{jj}, $\lvert\Delta\eta_{jj}\rvert$, $\Delta\phi_{jj}$	Invariant mass, difference in pseudorapidity, and signed difference in ϕ of the leading and subleading jets for events with at least two jets
Higgs boson and jet-related variables	
$p_T^{4\ell j}$, $m_{4\ell j}$	Transverse momentum and invariant mass of the four-lepton system and leading jet, for events with at least one jet
$p_T^{4\ell jj}$, $m_{4\ell jj}$	Transverse momentum and invariant mass of the four-lepton system and leading and subleading jets, for events with at least two jets

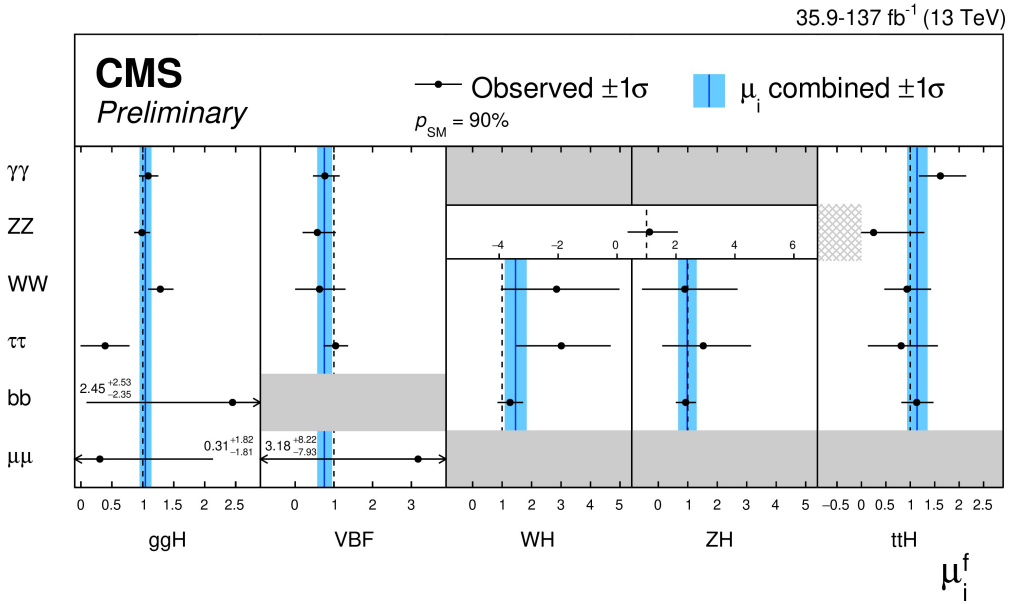
ATLAS H→ZZ probed distributions



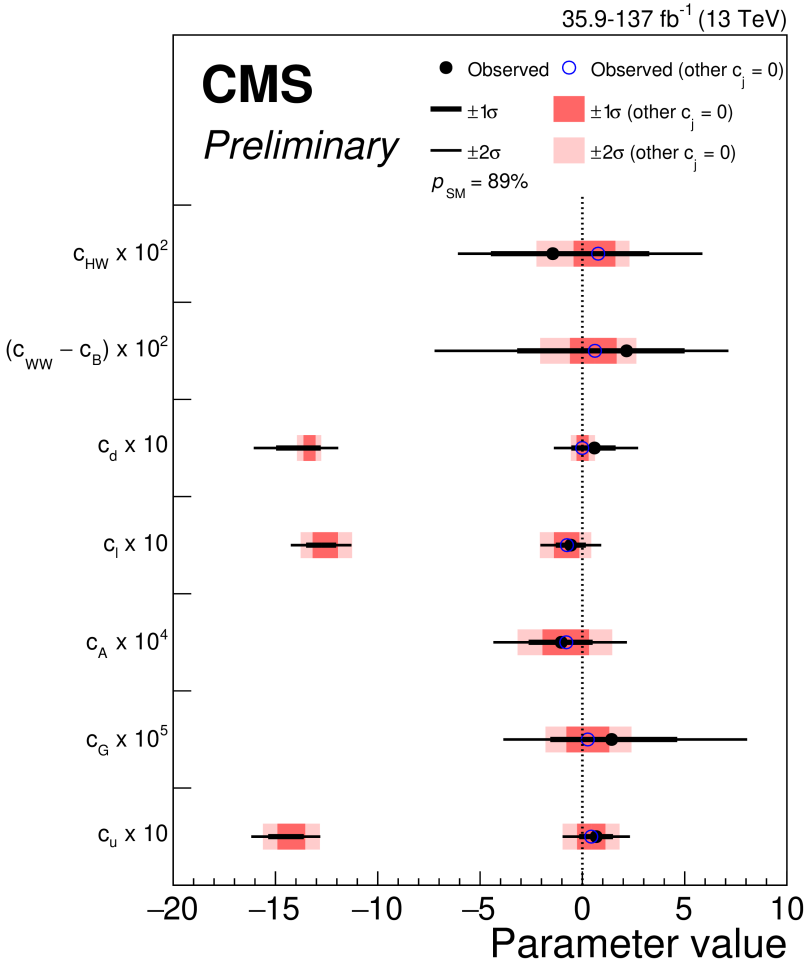
CMS H→ZZ STXS

CMS: Combination and EFT Limits

HIG-19-005



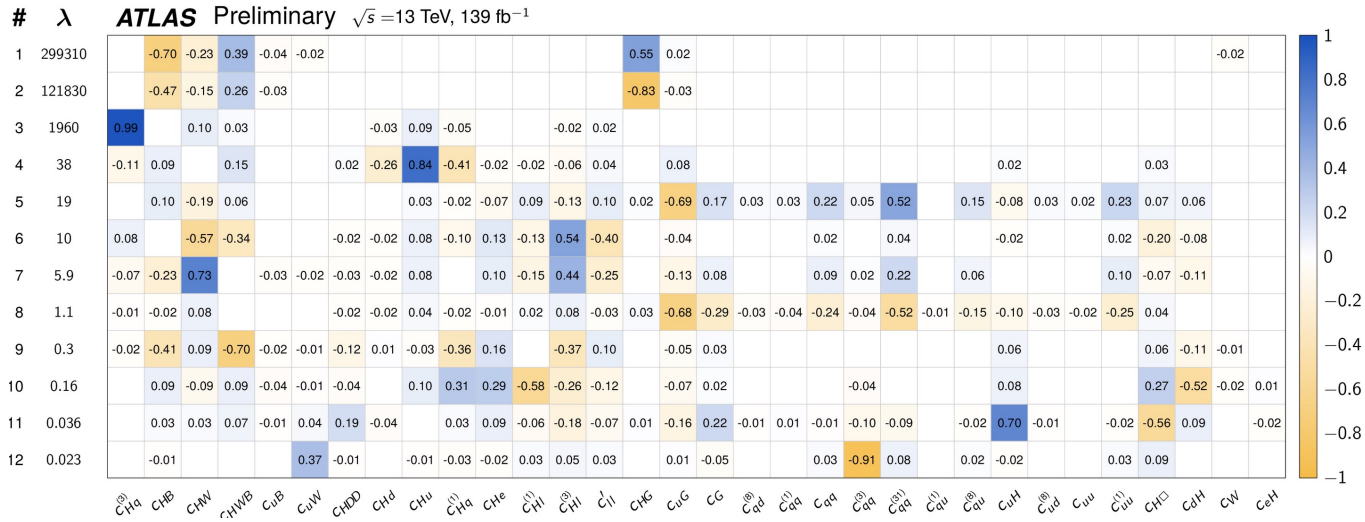
EFT coupling modifier limits

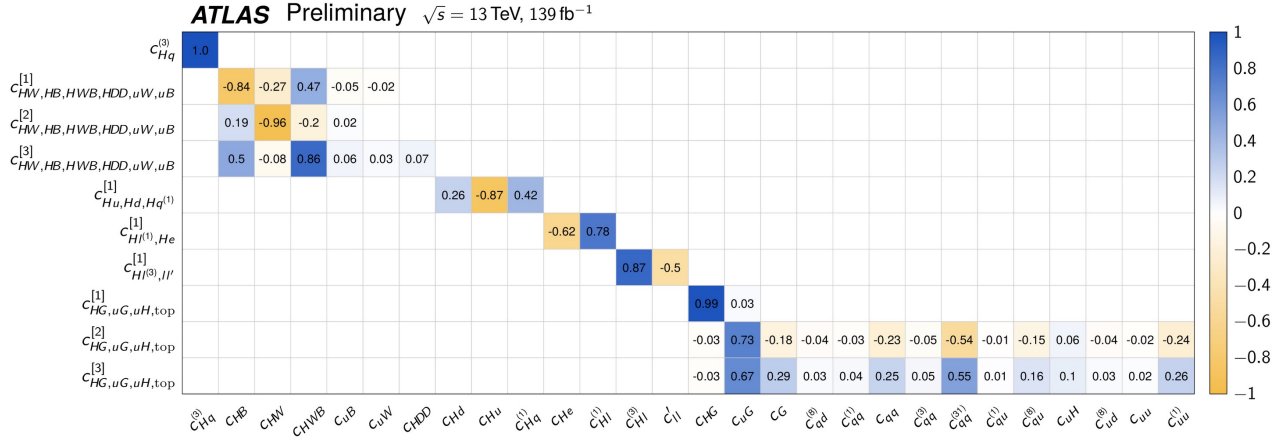


ATLAS: EFT Combination Eigenvectors

ATLAS-CONF-2020-053

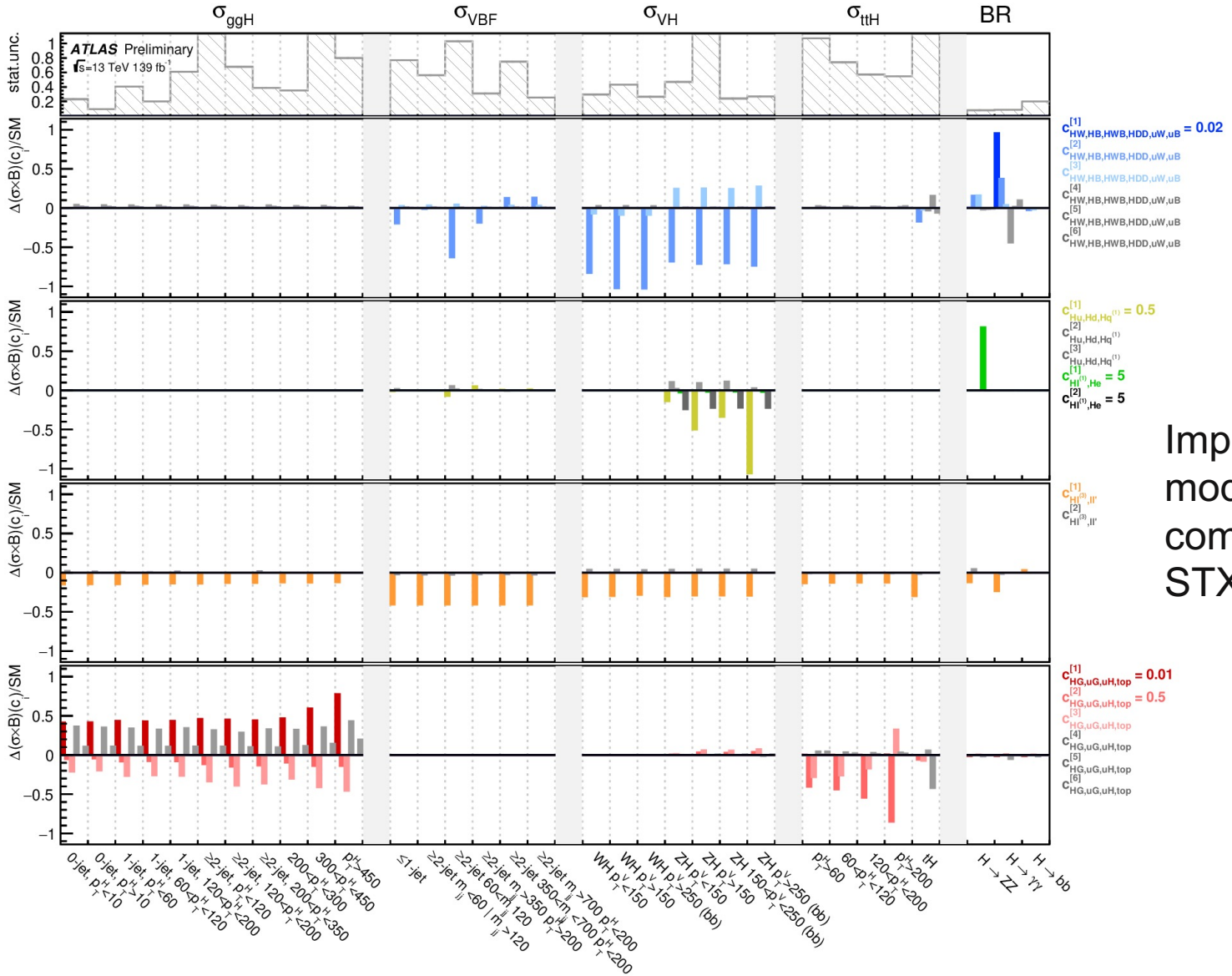
Building combinations of coupling coefficients (eigenvectors) to constrain multiple operators at once





ATLAS: EFT Combination

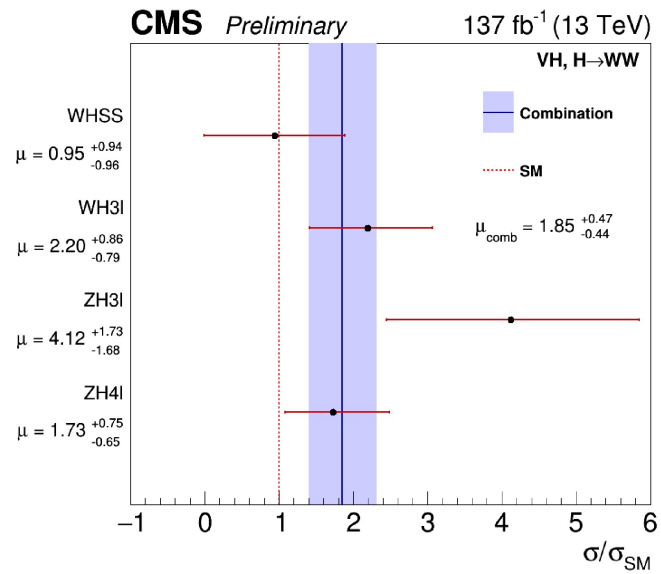
ATLAS-CONF-2020-053



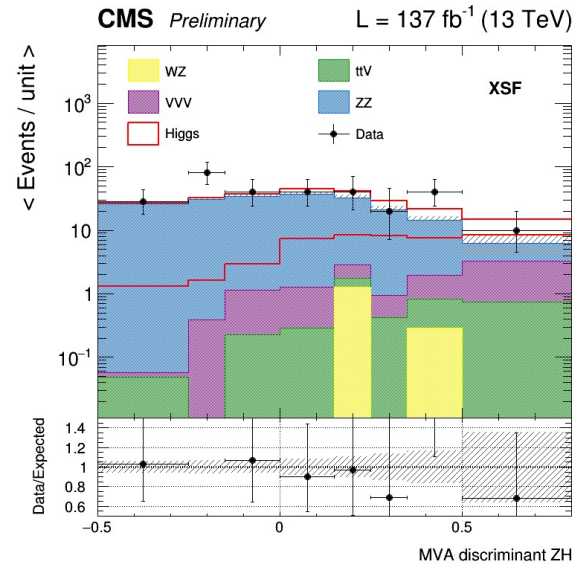
Impact of coupling modifier combinations on STXS bins

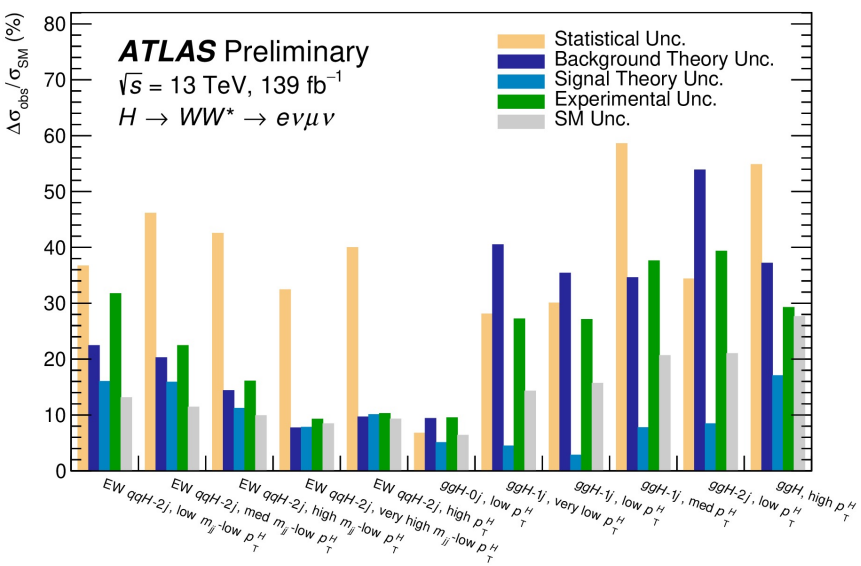
H→WW additional information

CMS VH(WW)



CMS ZH multivariate discriminant





ATLAS STXS uncertainties

HIG-19-017

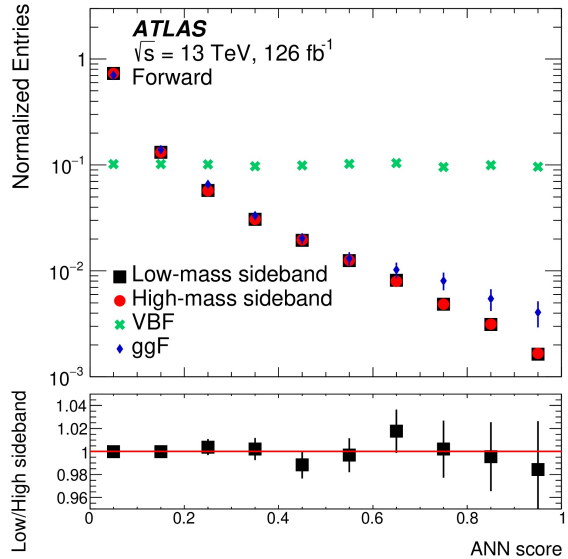
ATLAS-CONF-2021-014

+ VH and VBF H→bb additional information

ATLAS VH(bb) impact of uncertainties

Source of uncertainty		σ_μ VH	WH	ZH
Total		0.177	0.260	0.240
Statistical		0.115	0.182	0.171
Systematic		0.134	0.186	0.168
Statistical uncertainties				
Data statistical		0.108	0.171	0.157
$t\bar{t}$ $e\mu$ control region		0.014	0.003	0.026
Floating normalisations		0.034	0.061	0.045
Experimental uncertainties				
Jets		0.043	0.050	0.057
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.015	0.045	0.013
Leptons		0.004	0.015	0.005
b-tagging	b-jets	0.045	0.025	0.064
	c-jets	0.035	0.068	0.010
	light-flavour jets	0.009	0.004	0.014
Pile-up		0.003	0.002	0.007
Luminosity		0.016	0.016	0.016
Theoretical and modelling uncertainties				
Signal		0.072	0.060	0.107
Z + jets		0.032	0.013	0.059
W + jets		0.040	0.079	0.009
$t\bar{t}$		0.021	0.046	0.029
Single top quark		0.019	0.048	0.015
Diboson		0.033	0.033	0.039
Multi-jet		0.005	0.017	0.005
MC statistical		0.031	0.055	0.038

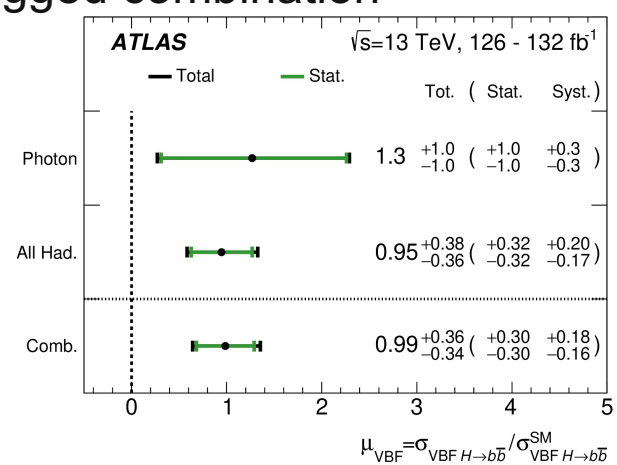
VBF Hbb categorization ANN output



arxiv:2011.08280

arxiv:2007.02873

VBF full hadronic and photon tagged combination

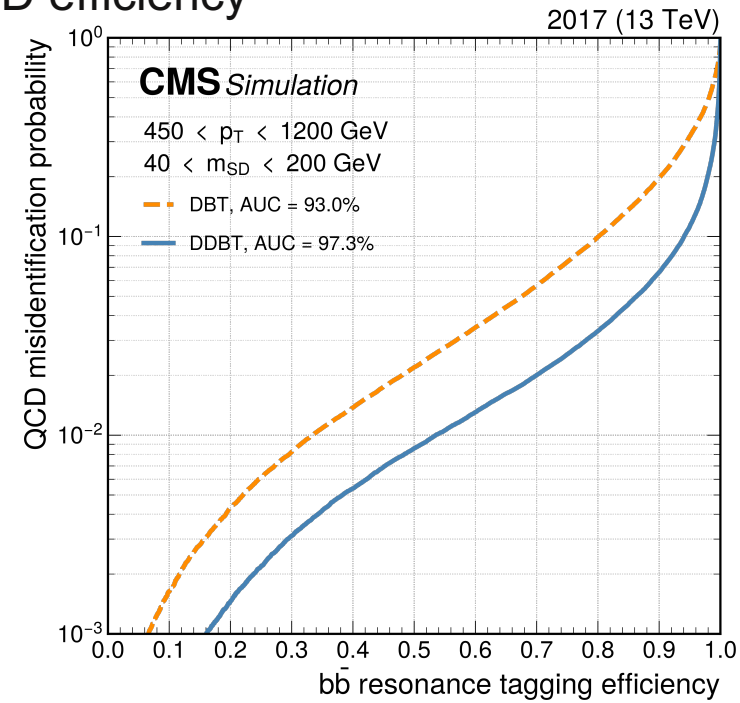


VBF full hadronic uncertainties

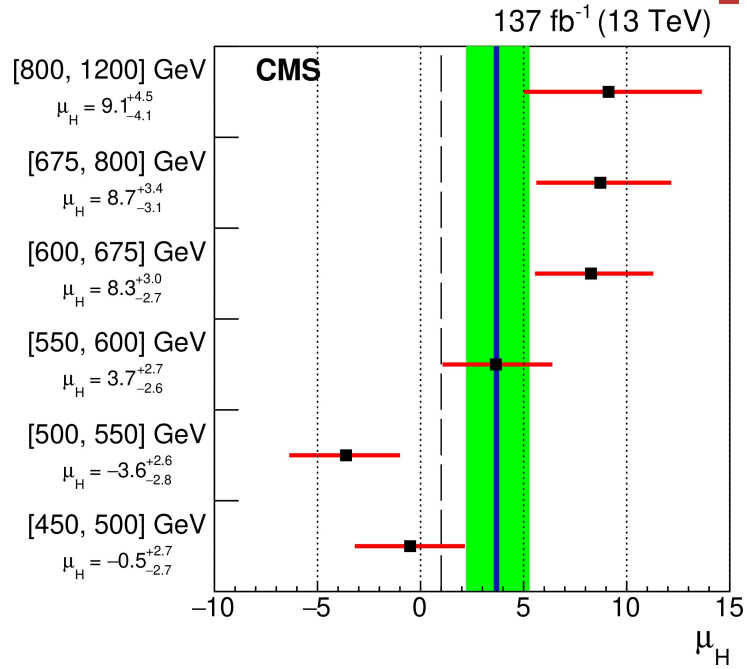
Uncertainty	$\sigma(\mu_{H\to b\bar{b}})$
Statistics	±0.31
NR Background Bias	±0.15
Embedded Z	±0.05
Experimental	+0.10/−0.05
Trigger	+0.07/ − 0.03
Jet	+0.06/ − 0.04
Flavor Tagging	+0.02/ − 0.01
Other	+0.02/ − 0.01
Signal Theory	+0.06/ − 0.03

H→bb at High pT

CMS double bb resonance ID efficiency



CMS ggF signal strength in pTH bins



ATLAS inclusive H→bb: contribution of different Higgs production channels

Process	p_T Range [GeV] 250–450	450–650	650–1000	> 1000
		SRL		
ggF	–	0.56	0.50	0.39
VBF	–	0.17	0.16	0.17
VH	–	0.14	0.18	0.25
$t\bar{t}H$	–	0.13	0.16	0.19
		SRS		
ggF	0.28	0.46	0.43	–
VBF	0.07	0.19	0.21	–
VH	0.26	0.24	0.26	–
$t\bar{t}H$	0.39	0.11	0.10	–

arxiv:006.13251

ATLAS-CONF-2021-010

+ ttH additional information

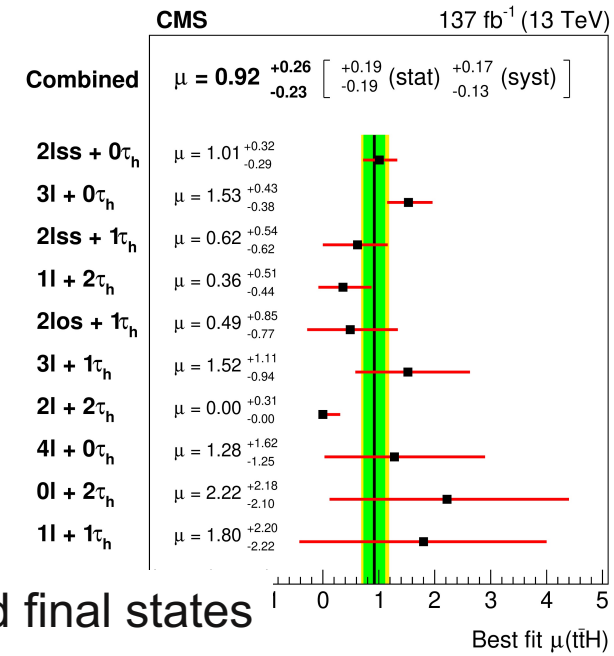
arxiv:2011.03652 ATLAS-CONF-2020-058

ATLAS ttH(bb) impact of uncertainties

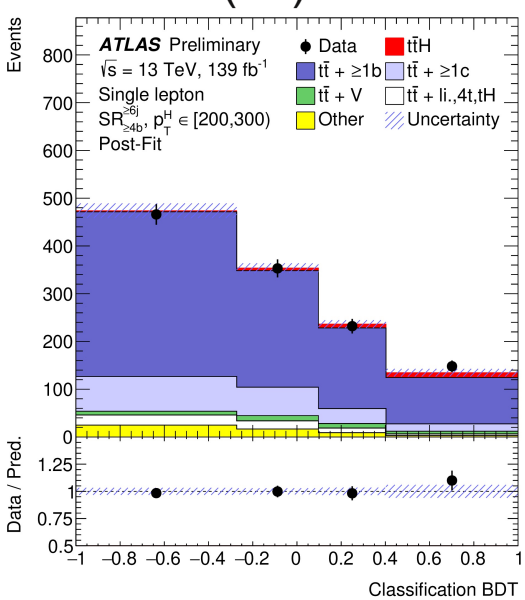
Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modelling	+0.25	−0.24
$t\bar{t}H$ modelling	+0.14	−0.06
tW modelling	+0.08	−0.08
b-tagging efficiency and mis-tag rates	+0.05	−0.05
Background-model statistical uncertainty	+0.05	−0.05
Jet energy scale and resolution	+0.03	−0.03
$t\bar{t} + \geq 1c$ modelling	+0.03	−0.03
$t\bar{t} +$ light modelling	+0.02	−0.02
Luminosity	+0.01	−0.00
Other sources	+0.03	−0.03
Total systematic uncertainty	+0.30	−0.27
$t\bar{t} + \geq 1b$ normalisation	+0.03	−0.05
Total statistical uncertainty	+0.20	−0.19
Total uncertainty	+0.36	−0.33

CMS ttH multi-lep. is stat. limited; second largest source of uncertainty MC norm

CMS ttH multi-lep. results per analysis channel



ATLAS ttH(bb) multivariate discriminant



CMS ttH multi-lep. targeted final states

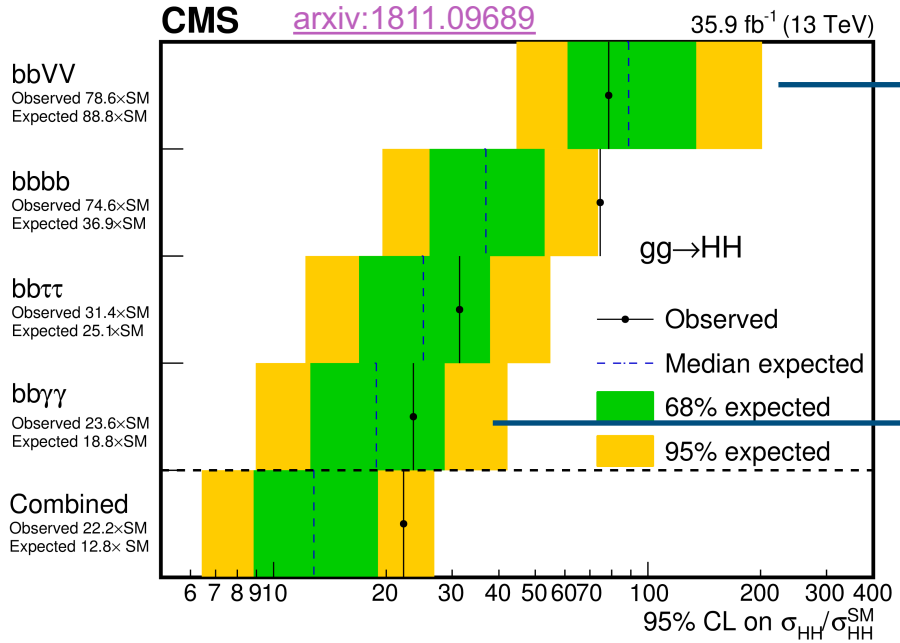
Selection step	$2\ell SS + 0\tau_h$	$2\ell SS + 1\tau_h$
Targeted $t\bar{t}H$ decay	$t \to b\ell\nu, t \to bqq'$ with $H \to WW \to \ell\nu qq'$	$t \to b\ell\nu, t \to bqq'$ with $H \to \tau\tau \to \ell\nu\nu\tau_h\nu$

Selection step	$3\ell + 0\tau_h$	$3\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu, t \to b\ell\nu$ with $H \to WW \to \ell\nu qq'$ $t \to b\ell\nu, t \to bqq'$ with $H \to WW \to \ell\nu\ell\nu$ $t \to b\ell\nu, t \to bqq'$ with $H \to ZZ \to \ell\ell qq'$ or $\ell\ell\nu\nu$	$t \to b\ell\nu, t \to b\ell\nu$ with $H \to \tau\tau \to \ell\nu\nu\tau_h\nu$

Selection step	$0\ell + 2\tau_h$	$1\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to bqq', t \to bqq'$ with $H \to \tau\tau \to \tau_h\nu\tau_h\nu$	$t \to bqq', t \to bqq'$ with $H \to \tau\tau \to \ell\nu\nu\tau_h\nu$

Selection step	$1\ell + 2\tau_h$	$2\ell + 2\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu, t \to bqq'$ with $H \to \tau^+\tau^- \to \tau_h\nu\tau_h\nu$	$t \to b\ell\nu, t \to b\ell\nu$ with $H \to \tau^+\tau^- \to \tau_h\nu\tau_h\nu$

Summary of SM HH Searches



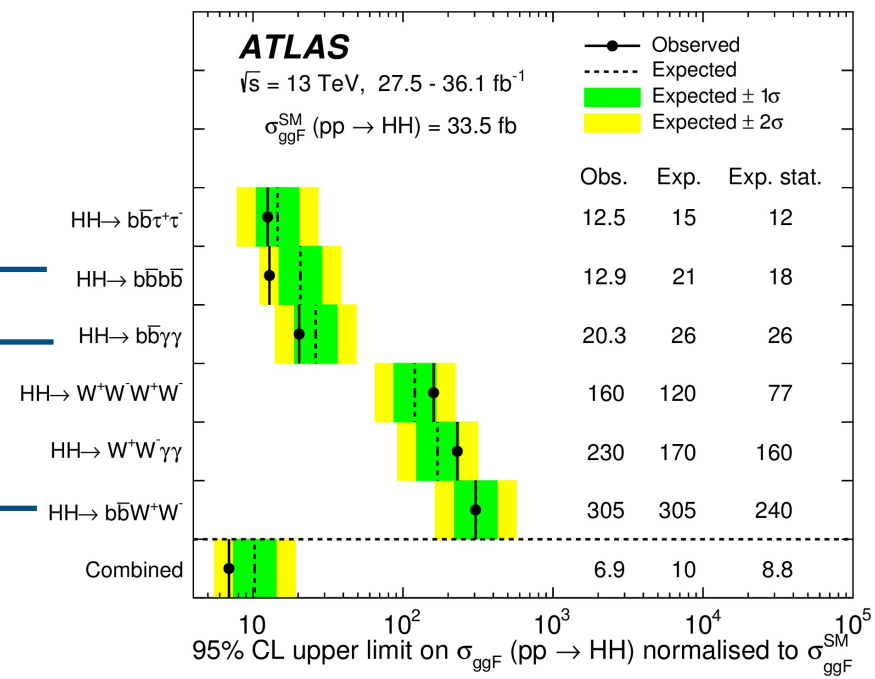
arxiv:1811.09689

Updated (bbZZ): 30*SM expectation

HIG-20-004

Updated: 7.7*SM expectation

arxiv:2011.12373



arxiv:2001.05178

New analysis added for VBF production

Updated: 4.1*SM expectation

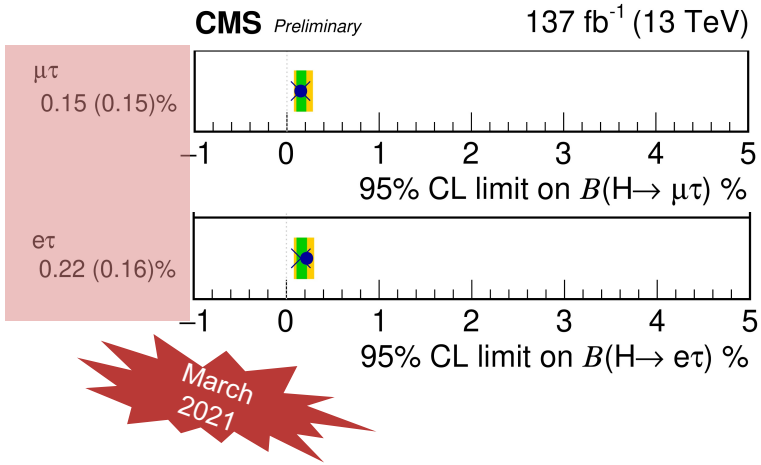
ATLAS-CONF-2021-016

Updated: 40*SM expectation

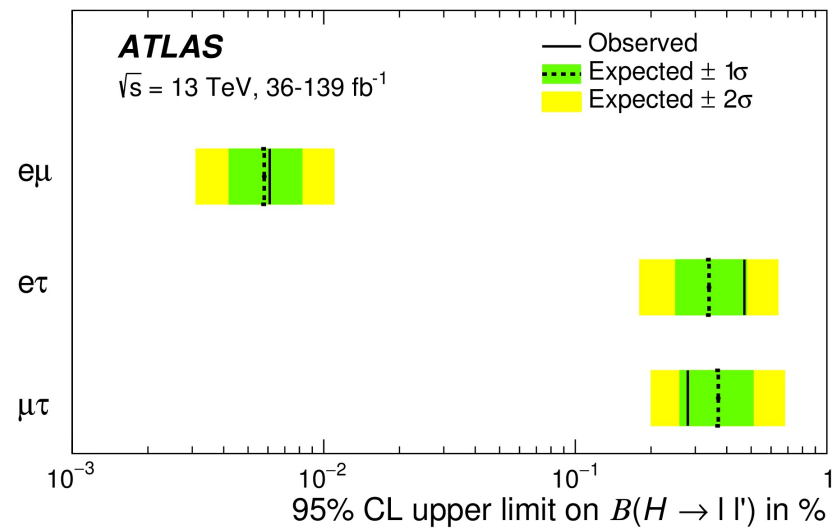
arxiv:1908.06765

Lepton Flavour Violating Decays and ee channel

Lepton flavour violating decays
m_H = 125 GeV HIG-20-009



H→$\mu\tau$ and H→eτ

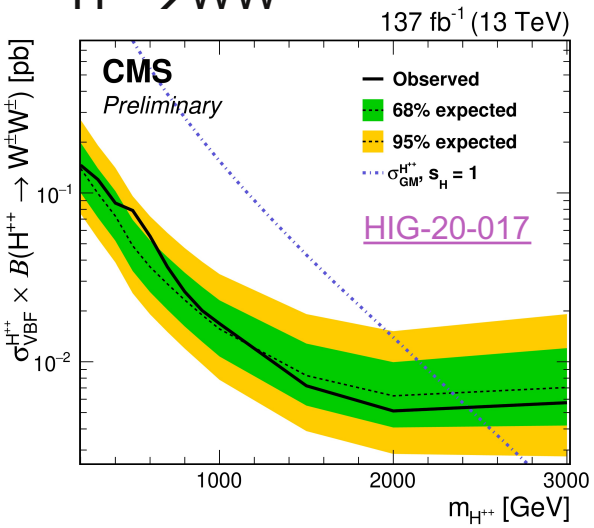


Phys. Lett. B 801 (2020) 135148

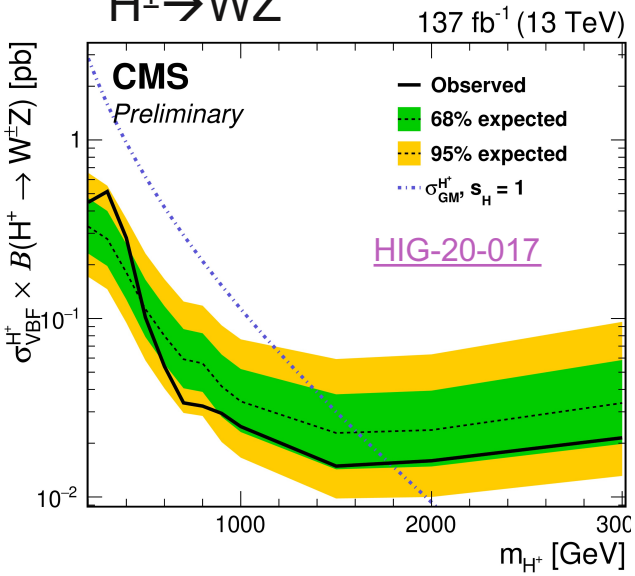
SM prediction
for BR(H→ee) = $5*10^{-9}$
→ ATLAS 95% CL limit:
BR(H→ee) < $3.6*10^{-4}$

Charged Higgs Bosons limits

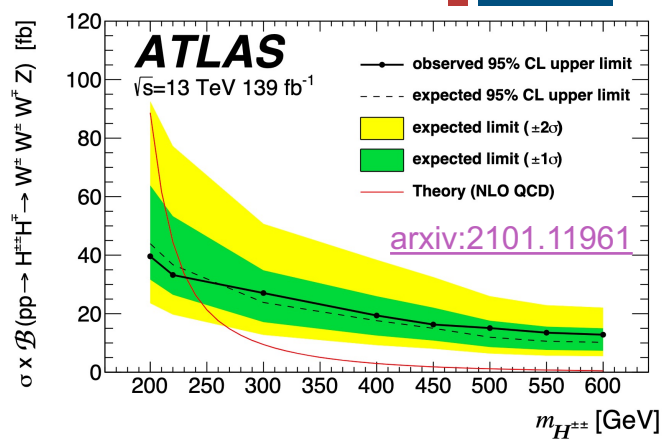
$H^{\pm\pm} \rightarrow WW$



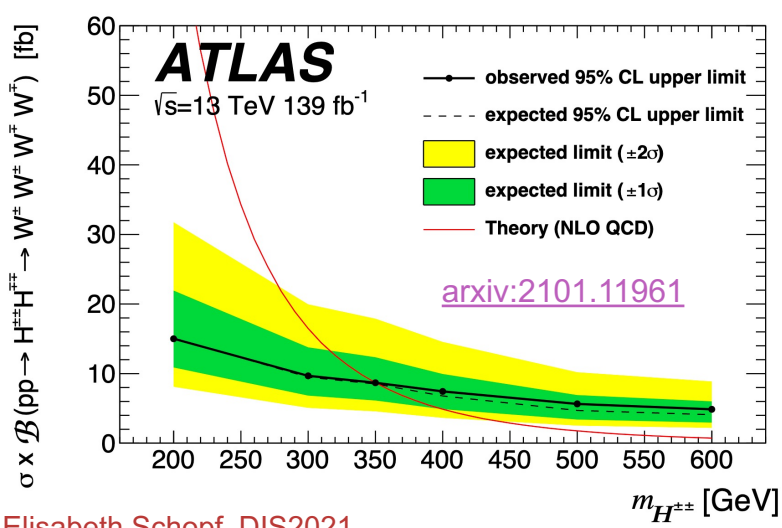
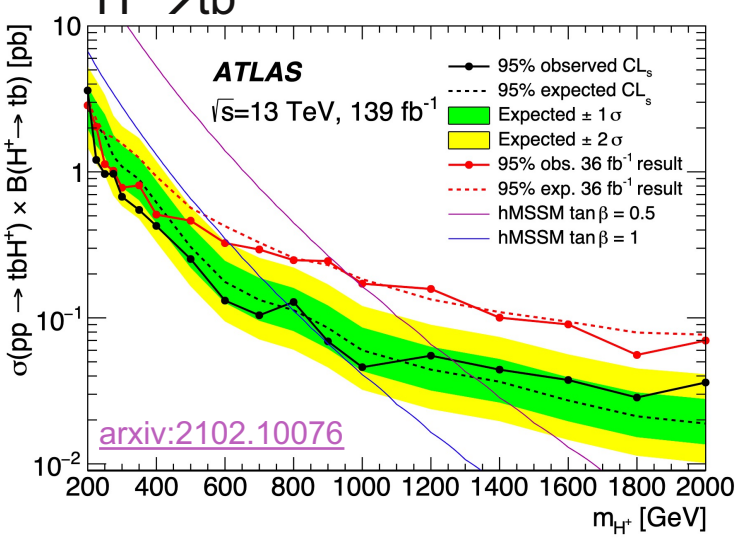
$H^{\pm} \rightarrow WZ$



$H^{\pm\pm}H^{\mp} \rightarrow WWWZ$



$H^{\pm\pm}H^{\mp\mp} \rightarrow WWWW$



$H^{+} \rightarrow tb$